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STEPHEN CRAMPTON
9 BROADFIELDS
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08620999001
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ROBOT CMM ARM

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ROBOT CMM ARM

FIELD OF THE INVENTION

The present invention concerns apparatus and method for a Robot CMM Arm for accurate measurement.

BACKGROUND TO THE INVENTION

Existing methods of automated measurement

Automated measurement of medium to large size objects requires a measuring machine accuracy of 0.05mm (+/- 2 Sigma) and typically 0.025mm (+/- 2 Sigma) or better. 'Sigma' means one standard deviation. It is currently carried out in two main ways: (i) a bulky, expensive, conventional Computer Numerically Controlled Coordinate Measuring Machine (CNC CMM) with 3 or more axes; (ii) a rigid structure of static Optical probes that is typically located in a dedicated cell at the end of the automotive production line. With a conventional CMM, the Optical probe moves in a highly controlled way around a static object to produce accurate data. In the second case, both Optical probes and object are static and localised in a calibrated way that permits accurate data. Most conventional CMMs are of either the moving bridge or horizontal arm structures; they are produced by companies including Zeiss (Germany), Hexagon Brown&Sharpe (Sweden) and LK (UK). Mechanical touch probes for mounting on conventional CMMs are supplied by companies including Renishaw (UK). Optical probes for mounting on conventional CMMs are supplied by companies including Metris (Belgium). Rigid structures of static Optical probes are supplied by Perceptron (USA). Both conventional CMMs and rigid structures of static Optical probes have the disadvantages that: they use up cell space on a production line that is typically only used for measurement and not a productive operation, they are usually situated at the end of the line, cannot feed forward data to downstream processes and are expensive and are difficult to justify on a payback basis. In addition, rigid structures of Optical probes are inflexible for rapidly changing models on the production line. Today, efficient production processes using robots that are quicker, better or cheaper than conventional processes but require high accuracy location cannot be deployed on the production line because of the disadvantages of existing high accuracy measurement systems.

Robot automated measurement

Since the 1960s, companies have developed heavy robot arms for applications requiring quick cycle times and repeatability. However, due mainly to temperature, wear and vibration problems, they have low accuracy. Robots have been used to carry probes for automated measurement. The robot arms are not accurate enough to meet the demanding requirements of most automated measurement, particularly in the automotive industry. The high repeatability of a robot arm has made 'quasi-static' measurement a solution that has received some uptake by the automotive industry. In 'quasi-static' measurement, the probe is moved from one position to the next and only takes data when static or moving slowly.

Measurement can be by either contact or non-contact probes. Measuring probes on robot arms tal three dimensional data from the surface of an object whilst moving at typical speeds of 10mm/sec – 200mm/sec (but can be more or less) are not accurate. Companies producing robot arms include Fanuc (Japan) and Kuka (Germany). Perceptron and LMI-Diffracto (USA) offer solutions using robot arms and Optical probes. 3D Scanners and Kuka showed a solution with real-time optical inspection at the Euromold 2001 exhibition in Frankfurt; its accuracy was of the order of 0.5-1mm. Standard industrial robots thermally grow by around 10 microns per degree Celsius temperature increase per meter of reach; errors in excess of 500 microns can be recorded in production line conditions. LMI-Diffracto have an automotive production line installation comprising four standard industrial robots supplied by Kuka, each carrying an Optical probe, wherein the robots are compensated for thermal growth, potentially reducing the thermal error in production line conditions to below 100 microns. In US patent 6,078,846 Greer assigned to Perceptron, compensation for robot thermal growth is carried out by measuring a fixed artefact with the Optical Probe. The Optical probes measure whilst the robot is static between movements. Error mapping has improved robot accuracy. There are several approaches including dancing the robot through a program of planned movements whilst measuring it with a photogrammetric system such as that from Krypton (Holland) or Northern Digital (Canada). The measurements are then used to create an error map. Error compensation for load has been carried out by measuring the power used by the servos to automatically calculate the loads on the arm. Even with multiple types of error compensation, accuracies of only 0.2mm (+/- 2 Sigma) have been achieved for robots of the type and reach found in large quantities on automotive production lines. The problem with robot arms carrying scanning probes in which there is relative movement between the probe and the object during scanning is that the systems are not accurate enough to be useful.

Tracking

In US patent 6,166,811 Long et al, a photogrammetry system for increasing the accuracy of scanning an object is disclosed in which photogrammetry targets affixed to the probe are tracked by a photogrammetry system in real-time. There are many disadvantages to this method. Firstly, a plurality of clear lines of sight need to be maintained between the probe and the photogrammetric cameras. In practice, lines of sight from the photogrammetry cameras to the photogrammetry targets on the probe are often blocked by the programmed robot movement and or the programmed changes in probe orientation necessary to scan the object. This so constrains the applicability of the system as to render it useless for many applications. Secondly, environmental lighting conditions must be maintained at a near ideal state or the accuracy of the photogrammetric system will reduce or the system will cease to function. In practice this is difficult to set up and often conflicts with other lighting requirements for the location. Thirdly, photogrammetric systems often do not have both the resolution and speed necessary for providing sufficient accuracy in this application. Fourthly, the photogrammetric cameras and the Robot must be mounted rigidly relative to each other. This often necessitates a stiff structure of large

dimensions to achieve the desired accuracy. The main problem with incorporating photogrammetric technology into a robot measuring system is that the resulting systems are not compact and robust enough to be useful.

Leica Geosystems supply the 6 degrees of freedom Laser Tracker LTD800. It can measure position and orientation over a 35m range with a single line of sight at up to 1000 measurements per second. Its accuracy is of the order of 50 microns for slow moving targets. Its cost is in excess of US$130,000. Many of its limitations for robot measuring are similar to those of photogrammetry. The main problems with incorporating laser tracker technology into a robot measuring system is that it is expensive, there are limitations to the orientation of the probe being tracked and the resulting systems are not compact and robust enough to be useful.

Robot controllers and programming

Controllers for robot arms are well understood by those skilled in the field; a standard reference work is 'Robot Manipulators, Mathematics Programming and Control' by Richard P Paul. Adept Technologies (US) supply 6-axis robot controllers starting at US$8,500. There are many products available for the programming of robots that allow motion sequences to be generated off-line and subsequently communicated to the Robot Controller for later execution; one example is EmWorkplace from Tecnomatix (US).

Manual CMM Arms

Since the 1970's, companies have been building manually operable CMM arms that have recently achieved a measuring accuracy using a contact probe of between 0.025 mm (+/- 2 Sigma) and 0.005 mm (+/- 2 Sigma) depending, mainly, on the reach of the Manual CMM Arm. Manual CMM Arms are expected to become more accurate with further development. These Manual CMM Arms are now accurate enough for many measurement requirements and are a growing sector in the measurement marketplace. They have the flexibility of being able to get into areas with difficult access. Manual CMM Arms are acceptably accurate for many applications, but are not automated; they are expensive to operate, particularly since a semi-skilled operator is required; human operators are also subject to human error. Manual CMM Arms are produced by companies including: Cimcore (USA), Faro Technologies (USA), Romer (France) and OGP (UK). As examples, US Patent 3,994,798 Eaton, US Patent 5,402,582 Raab assigned to Faro Technologies, US Patent 5,829,148 Eaton and US Patent 6,366,831 Raab assigned to Faro Technologies disclose background information on Manual CMM Arms. The provision of bearings at the joints of Manual CMM Arms is well known and US Patent Application 2002/0087233 Raab assigned to Faro Technologies discloses background information on bearings. The design of Manual CMM arms is typically limited to around 2 metres in reach from the centre of joint 1 to the probe tip because any longer and it requires two operators to use the arm. The longer the Manual CMM

arm is, the less accurate it is. In general, for a modular Manual CMM Arm design all other things be equal, the accuracy is inversely proportional to the length. In US Patent 6,366,831 Raab, it is disclosed that in the field, Manual CMM Arms typically have an absolute positional accuracy ten or more times that of a robot arm. Some of the factors in robots that cause inaccuracy including joint misalignments are referred to in US Patent 6,366,831. Manual CMM arms such as those manufactured by Faro Technologies and Romer are generally operated by a single person using both hands. Each of the operator's hands provides a different 6 DOF action on the segment of the Manual CMM arm that is gripped by the hand. Some skilled operator's may only need one hand in some applications. A Manual CMM arm is a mechanism that is controlled in a closed-loop fashion wherein the operator closes the loop. Such control is a skilled activity; the operator needs to control 6 or 7 axes of arm freedom in a variety of different spatial geometries, under the effect of gravity, with just two hands. It is often the case that the operator mishandles the Manual CMM arm and part or all of the Manual CMM arm accelerates under gravity until there is a collision or the operator steadies it. It is the case that during data capture, the operator applies variable and occasionally excessive forces and torques on the Manual CMM arm, which reduce the accuracy of the measurement data the Manual CMM arm outputs.

Counterbalances

A Manual CMM Arm typically has a compensating device built into the second joint that provides a torque on the upper arm that tends to provide a lifting force on the upper arm to counterbalance it. Counterbalances for manual CMM arms are disclosed in US Patents 6,298,569 Raab et al and 6,253,458 Raab et al, both assigned to Faro Technologies. This means that the arm is lighter for the operator to lift and is consequently less tiring to use. This also means that more torque is transmitted through the Manual CMM Arm and requires that the Manual CMM Arm must be designed to be heavier than without such a compensating device to achieve a required accuracy. It is standard practice to counterbalance Robots.

Optical probes on Manual CMM Arms

Optical probes on Manual CMM Arms were disclosed by Crampton, the inventor of the present invention, in several patent applications including WO9705449. Optical probes for Manual CMM Arms are provided or are being developed by 3D Scanners, Romer, Faro Technologies, Perceptron, Steinbichler (Germany), Pulstec (Japan) and Kreon (France) amongst others. Optical probes are generally mounted offset on the side of the Manual CMM Arm or mounted on the probe end of it. There are three broad types of Optical probe: point, line and area. As yet, a measurement accuracy standard does not exist that defines the way accuracy should be measured for point, line and area Optical probes. The marketplace is in the situation of not being able to perform standard tests to verify accuracy and enable comparison between Optical probe types in a practical way. Optical probes have become accurate, largely because there measuring range is short. In general, Optical probes gather measurement

data over a measuring range of the order of 20-400 mm. This is often at a standoff to the end of the Manual CMM Arm. The accuracy of the best Manual CMM Arms combined with the best Optical probes is already better than 0.050 mm (+/- 2 Sigma) and can be better than 0.010 mm (+/- 2 Sigma) or even 0.002 mm (+/- 2 Sigma) for short measuring ranges.

Synchronisation and interpolation of Optical probes on Manual CMM Arms

In a system comprising a Manual CMM Arm and an Optical probe, measurements from each are combined to give the output measurement data. As disclosed in WO9705449 by Crampton, the inventor of the present invention, the measurement accuracy of a system comprising a Manual CMM Arm and an Optical probe is increased by synchronising the timing of a measurement from the Manual CMM Arm and a measurement from the Optical probe. As further disclosed in WO9705449, alternatively, the measurement accuracy of a system comprising a Manual CMM Arm and an Optical probe is increased by time-stamping each measurement from the Manual CMM Arm and time-stamping each measurement from the Optical probe and later using a process of interpolation of the two sets of measurements to provide a combined set of measurements.

Calibration and Alignment of Robots and Manual CMM Arms

As disclosed in US Patent 5,687,293 Snell, a robot can be calibrated using a reference sphere and a spherically tipped probe on the robot by bringing the spherically tipped probe into contact with the reference sphere a number of times with different robot spatial layouts; a 39-parameter kinematic model for a 6-axis robot embodiment is disclosed. The alignment of Optical probes to Robots is disclosed in US Patent US 6,321,137B1 De Smet. A method of calibrating a Manual CMM Arm is disclosed in US Patent 5,402,582 Raab assigned to Faro Technologies. Some Manual CMM Arms are calibrated by the manufacturer before shipping. These suppliers, including Faro Technologies, enable the user to perform a simple probe calibration each time the probe is changed, whilst the Manual CMM Arm calibration remains the same. OGP UK supply the Polar Manual CMM Arm and permit the user to fully calibrate the Polar arm and probe together in a simple procedure by using a reference artefact with several cones into which the spherical probe of the Polar arm is placed whilst the arm is exercised through a variety of spatial layouts; a 39-parameter kinematic model is used for their 6-axis Polar arm. The alignment of Optical probes to Manual CMM Arms is disclosed in WO9705449 by Crampton, the inventor of the present invention.

Attachment of Robots and Measuring devices

As disclosed in US Patent 5,392,384 Tounai et al, the tip of a 6 axis articulated measuring device is attached to the tip of a robot for the purpose of calibrating the robot. As disclosed in US Patent 6,519,860 Bieg et al, the tip of a 3 axis articulated measuring device is attached to the tip of a robot or machine for the purpose of measuring the spatial performance of the robot or machine. Neither of these

disclosures is used to measure an object. As disclosed in WO 98/27887 Wahrburg, a surgical robot a multiple joint sensor arm are attached at the base; the multiple joint sensor arm is used manually to make measurements on the patient, a robot program is generated based on those measurements and the robot carries out the surgical intervention. In this disclosure the measurement is not automated.

Need for automation

A Manual CMM Arm with an Optical probe is typically used for many hours at a time. During much of this time, the operator holds the Manual CMM Arm at a distance from him, often in awkward locations. The weight that is supported at a distance can be several kilograms for a long Manual CMM Arm. This is hard work and is tiring for many operators, particularly smaller people; operator fatigue is a common problem and this can lead to illness, incapacitation or injury. Much of the work done with Manual CMM Arms is for unique components that only need to be optically inspected once. Often, the surface being inspected is not immediately accessible and requires temporary gantries to be erected for the operator to climb on so that the arm can be manipulated. The problem with Manual CMM Arms carrying scanning probes in which there is relative movement between the probe and the object during scanning is that, although they are accurate enough, the system is fatiguing to use and can output inaccurate data through operator error or over-stressing of the Manual CMM Arm, because it cannot operate automatically.

Need for accessibility

The shape of objects to be measured and their accessibility to a probe on a movable member vary from application to application. A CMM that is flexible enough to access a larger range of object shapes has more utility. In practice, it is generally established that articulated arm CMMs comprising a series of preferably 6 or 7 joints separated by rigid segments are more flexible than orthogonal axis configuration CMMs. It is also generally established in the existing state of the art that automated orthogonal axis configuration CMMs are several orders more accurate than automated articulated Robot arms. It is also generally established that automated orthogonal axis configuration CMMs are less suitable than automated articulated arm Robots for locating in a manufacturing environment such as on an assembly line. The problem is that no automated CMM machine is available that is articulated and sufficiently accurate.

Need for portability

As exhibited by the purchase of the order of 5,000 portable Manual CMM Arms since they became accurate enough in the mid-1990's, there is a significant demand for portable Manual CMM Arms. There is a corresponding need for a portable Automated CMM Arm, but none exist today.

SUMMARY OF THE INVENTION

It is a purpose of this invention to provide a Robot CMM Arm means of measurement that is accurate and automated. In a first embodiment of this invention, the Robot CMM Arm comprises a Robot Exoskeleton that encloses an Internal CMM Arm and manipulates the Internal CMM Arm via transmission means such that it can carry out measurement. The Robot CMM Arm and the Internal CMM Arm are rigidly attached at the base. The Robot Exoskeleton and the Internal CMM Arm have the same joint axis orientations and joint centres. The Robot CMM Arm has preferably 6 or 7 axes. There is a transmission means between each Robot Exoskeleton segment and the corresponding Internal CMM Arm segment. Each transmission means is preferably located as close as practicable to the centre of gravity of the corresponding Internal CMM Arm segment. At least one probe is mounted on the probe end of the Internal CMM Arm. A Probe can be either a contact probe or a non-contact probe. A non-contact Probe is preferably a stripe Probe. Positions from the Internal CMM Arm and measurements from the Probe are combined. The Internal CMM Arm and the Probe are synchronised. Alternatively, data from the Internal CMM Arm and the Probe are time stamped. Strain gauges are attached to each segment of the Internal CMM Arm. The transmission means are soft. A control box is integrated into the base of the Robot CMM Arm. Alternatively, the control box is a separate unit. At least one Tool can be mounted on the probe end of the Internal CMM Arm. It is a further purpose of this invention to provide a method for positioning the Robot CMM Arm to measure data of an object. A method is provided for synchronising the probe data and the position data. A method is provided for time stamping the probe data and the position data. This Robot CMM Arm invention has a novel structure, and novel capabilities that none of Robots, Manual CMM Arms or Conventional CMMs are capable of.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1A is a schematic diagram for a 6-axis Robot CMM Arm in accordance with a first embodiment of the present invention;

Figure 1B is a schematic diagram for a 7-axis Robot CMM;

Figure 1C is a layout for a Robot CMM Arm system;

Figure 2 is a schematic diagram of the Joints and Segments of the Robot Exoskeleton and the Internal CMM Arm;

Figure 3 is a schematic diagram of the reach of a Robot CMM Arm;

Figure 4 is a schematic diagram of the virtual reach of a Robot CMM Arm with an Optical probe;

Figure 5A is a schematic diagram of a long CMM Segment;

Figure 5B is a schematic diagram of a short CMM Segment;

Figure 5C is a schematic diagram of CMM Segment 8;

Figure 5D is a schematic diagram of the base;

Figure 5E is a layout of separate base segments that are separately mounted;

Figure 5F is a layout of separate base segments that are mounted on the same surface;

Figure 5G is a layout of the Robot Exoskeleton base mounted on a surface;

Figure 5H is a layout of a common base;

Figure 6 is a schematic diagram of a stand;

Figure 7A is a layout of a Robot CMM Arm mounted on a vibration isolated table;

Figure 7B is a layout of a floor mounted Robot CMM Arm;

Figure 7C is a layout of a Robot CMM Arm mounted on a surface plate embedded in the floor;

Figure 7D is a layout of a Robot CMM Arm mounted on a linear rail;

Figure 8A is a layout of a Robot CMM Arm mounted on a wall;

Figure 8B is a layout of a Robot CMM Arm mounted on a gantry;

Figure 8C is a layout of a Robot CMM Arm mounted on an inclined platform;

Figure 8D is a layout of a Robot CMM Arm mounted on a horizontal arm CMM;

Figure 8E is a layout of a Robot CMM Arm mounted on a moving bridge CMM;

Figure 9 is a layout of a Robot CMM Arm with a photogrammetric tracker;

Figure 10 is a detailed layout for a Robotic CMM Arm system;

Figure 11 is a diagram of the architecture of a Robotic CMM Arm;

Figure 12 is a schematic diagram of an encoder;

Figure 13 is a schematic diagram of forced air circulation;

Figure 14 is a schematic diagram of the location of all the transmission means;

Figure 15 is a schematic diagram of the location of the Segment 8 transmission means;

Figure 16 is a schematic diagram of the location of the Segment 7 transmission means;

Figure 17 is two sections of radial transmission means;

Figure 18 is two sections of torsional transmission means;

Figure 19 is a schematic of a counterbalance;

Figure 20 is a schematic diagram of hard limits and limit switches in an axial joint;

Figures 21A and 21B are schematic diagrams of hard limits in an orthogonal joint;

Figure 22 is a schematic diagram of bearings;

Figure 23 is a view and a section of the probe end of the Internal CMM Arm;

Figure 24 is a longitudinal section of a touch trigger probe mounted on the probe end;

Figure 25 is a longitudinal section of an optical probe mounted on the probe end;

Figure 26 is a view of the optical probe and bracket;

Figure 27A is a diagram of the architecture of the probe;

Figure 27B is a schematic diagram of a probe connected to three cables and a probe box;

Figure 27C is a layout of a probe with one cable to a probe box running exterior to the Robot CMM Arm;

Figure 27D is a layout of a probe with a probe box connected through the Robot CMM Arm;

Figure 28 is a two view schematic diagram of the principle of a stripe probe;

Figure 29 is a schematic diagram of a stripe probe scanning;

Figure 30 is a schematic diagram of the measuring areas of a stripe;

Figure 31 is a schematic diagram of a patch of stripes;

Figure 32 is a schematic diagram of a number of overlapping patches;

Figure 33A is a schematic diagram of a two-view stripe probe;

Figure 33B is a schematic diagram of a two-view stripe probe scanning a stepped object;

Figure 34A is a schematic diagram of a two-stripe probe;

Figure 34B is a schematic diagram of a two-stripe probe scanning the vertical wall of a stepped object;

Figure 35 is a schematic diagram of a platform for a laptop;

Figure 36 is a schematic diagram of a pendant;

Figure 37 is a schematic diagram of a headset on an operator;

Figure 38A is a layout of buttons on a Robot CMM Arm;

Figure 38B is a layout of footswitches;

Figure 38C is a layout of a remote control with strap;

Figure 39 is a layout of coordinate systems;

Figure 40 is a diagram of the architecture of the Control PCB;

Figure 41 is a diagram of the architecture of the Joint PCB;

Figure 42 is a flow diagram for a synchronisation process with the Probe as Master;

Figures 43A, 43B and 43C are timing diagrams for probe measurment;

Figure 44 is a timing diagram showing the delay of a triggered probe measurement;

Figure 45 is a flow diagram for a synchronisation process with the Probe as Slave;

Figure 46 is a flow diagram for a time stamping measurement process;

Figure 47 is a schematic diagram of a probe scanning a ridged artefact;

Figure 48 is a diagram of +X and -X scans of the ridged artefact;

Figure 49 is a layout of calibration equipment;

Figure 50 is a diagram of a calibration artefact;

Figure 51 is a location diagram for positioning the calibration artefact;

Figure 52 is a flow diagram of a measuring process.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

General description

This Robot CMM Arm invention comprises an Internal CMM Arm guided by a Robot Exoskeleton. The Robot Exoskeleton supports and manipulates the Internal CMM Arm via transmission means such that it can measure accurately. This invention can be embodied in many Robot CMM Arm articulated arm layouts. There are two preferable layouts for a Robot CMM Arm in accordance with a first embodiment of the present invention: 6-axis with 6 joints and 7-axis with 7 joints.

Robot CMM Arm Joint and segment layout

Figures 1A and 1B are diagrams showing the preferable 6-axis and 7-axis layouts respectively for a Robot CMM Arm 1 in accordance with a first embodiment of the present invention. An articulated arm has a base end 2 and a probe end 3 and comprises a series of segments and rotating joints between the two ends. There are two types of joint: axial and orthogonal. An axial joint (labelled 'A' in Figures 1A, 1B) rotates about the common axis of its two adjoining segments. An orthogonal joint (labelled 'O' in Figures 1A and 1B) rotates as a hinge between its two adjoining segments. In Figure 1A, the type of joints in order from the base end 2 to the probe end 3 is AOOAOA referring respectively to joint centres 21, 22, 24, 25, 26 and 27. In Figure 1B, the type of joints in order from the base end 2 to the probe end 3 is AOAOAOA referring respectively to joint centres 21, 22, 23, 24, 25, 26 and 27. The 6-axis layout has the advantage of lower cost. The 7-axis layout has the advantage of increased flexibility for access to complex objects.

The preferable 7-axis Robot CMM Arm 1 layout of Fig 1B is described in this first embodiment of the Robot CMM Arm 1 invention, but the invention is not limited to this joint layout or the preferable 6-axis layout of Fig 1A and can have more or less joints than 7. For a simple application, 3 joints can be sufficient. This invention is not limited to only rotational axes of movement. As will be disclosed later, it can comprise one or more linear axes of movement to which the base end 2 is preferably attached.

Figure 1c shows the Robot CMM Arm system 150 comprising a Robot CMM Arm 1, connected to a laptop 151 with a cable 152. The Robot CMM Arm 1 has a base end 2 and a probe end 3. It is mounted on a surface 7. A probe 90 is mounted on the probe end 3 of the Robot CMM Arm 1. An Optical probe 91 is also mounted towards the probe end 3 of the Robot CMM Arm 1. The Robot CMM Arm 1 comprises a base 4, an Internal CMM Arm 5, a Robot Exoskeleton 6 and Transmission Means 10. The object 9 being measured is situated on the surface 7.

Figure 2 shows the two main parts of the Robot CMM Arm 1: the Internal CMM Arm 5 and the Robot Exoskeleton 6 sharing a common base 4 and common joint centres 21, 22, 23, 24, 25, 26 and 27. The

Internal CMM Arm 5 comprises segments 32, 33, 34, 35, 36, 37 and 38 referred to in the text as CMM Segment2-8 respectively. CMM Segment8 38 reaches to the probe end 3 of the Robot CMM Arm 1. The common base 4 is also referred to as CMM Segment1 31. The Internal CMM Arm 5 further comprises joints 51, 52, 53, 54, 55, 56, 57 referred to in the text as CMM Joint1-7 respectively. The Robot Exoskeleton 6 comprises segments 42, 43, 44, 45, 46, 47 and 48 referred to in the text as Robot Segment2-8 respectively. Robot Segment8 48 does not reach to the probe end 3 of the Robot CMM Arm 1. The common base 4 is also referred to as Robot Segment1 41. The Robot Exoskeleton 6 further comprises joints 61, 62, 63, 64, 65, 66 and 67 referred to in the text as Robot Joint1-7 respectively. The Robot CMM Arm 1 further comprises Transmission Means 72, 73, 74, 75, 76, 77 and 78 referred to in the text as Transmission Means2-8 respectively, attaching Internal CMM Arm 5 to Robot Exoskeleton 6. Transmission Means2 72 attaches CMM Segment2 32 to Robot Segment2 42. Transmission Means3 73 attaches CMM Segment3 33 to Robot Segment3 43 and so on correspondingly for Transmission Means4-8 74, 75, 76, 77 and 78.

Internal CMM Arm joint and segment layout

The segments and joints of the Internal CMM Arm 5 in the Robot CMM Arm 1 are named and laid out in general terms as follows.

Segment	Name	Location description	Comparative Length
CMM Segment 1	Base	Between base end and Joint 1	Short
CMM Segment 2	Shoulder	Between Joint 1 and Joint 2	Short
CMM Segment 3	Upper Arm	Between Joint 2 and Joint 3	Long
CMM Segment 4	Elbow	Between Joint 3 and Joint 4	Short
CMM Segment 5	Lower Arm	Between Joint 4 and Joint 5	Long
CMM Segment 6	Hand	Between Joint 5 and Joint 6	Short
CMM Segment 7	Wrist	Between Joint 6 and Joint 7	Short
CMM Segment 8	Probe	Between Joint 7 and probe end	Short

Joint	Name	Type	Rotation
CMM Joint 1	Base	Axial	>360 degs
CMM Joint 2	Shoulder	Orthogonal	>180 degs
CMM Joint 3	Pre-elbow	Axial	>360 degs
CMM Joint 4	Elbow	Orthogonal	>180 degs
CMM Joint 5	Pre-wrist	Axial	>360 degs
CMM Joint 6	Wrist	Orthogonal	>180 degs
CMM Joint 7	Sensor	Axial	>360 degs

Referring now to **Figure 3**, the Reach 80 of the Robot CMM Arm 1 is defined as being from J. Centre2 22 to the probe end 3 of CMM Segment8 38, when the CMM Joints3-7 are rotated to maximise this distance. The bulk of the Reach 80 of the Robot CMM Arm 1 comprises the sum of the lengths of CMM Segment3 33 and CMM Segment5 35.

Referring now to **Figure 4**, in the case where an Optical probe 91 is mounted on CMM Segment8 38, the reach 80 is increased with a virtual reach 81 of the distance between the probe end 3 of CMM Segment8 38 and the Optical measuring mid-point 82 of the measuring depth over which measurements can be taken.

Each CMM Segment has a high stiffness. Any bending or torsion in a segment will reduce the accuracy of the Internal CMM arm 5. A typical maximum angular torsional strain in a CMM segment of the Robot CMM Arm in normal use is 0.25 arc second, but could be more or less, particularly depending on the length of the CMM Segment. A typical maximum angular bending strain in a CMM Segment of the Robot CMM Arm in normal use is 0.25 arc second, but could be more or less, particularly depending on the length of the CMM Segment.

Each CMM Segment comprises one or more significant items:

Segment	**Item**	**Joints**	**Description**
CMM Segment 1	Base	1	Machined aircraft aluminium
CMM Segment 2	Shoulder	1,2	Machined aircraft aluminium
CMM Segment 3	Housing	2	Machined aircraft aluminium
	Link	0	Woven carbon fibre
	Housing	3	Machined aircraft aluminium
CMM Segment 4	Elbow	3,4	Machined aircraft aluminium
CMM Segment 5	Housing	4	Machined aircraft aluminium
	Link	0	Woven carbon fibre
	Housing	5	Machined aircraft aluminium
CMM Segment 6	Hand	5,6	Machined aircraft aluminium
CMM Segment 7	Wrist	6,7	Machined aircraft aluminium
CMM Segment 8	Probe	7	Machined aircraft aluminium

Referring now to **Figure 5A**, CMM Segments3,5 33, 35 comprise a Link Member 102 with diameter 108 and wall thickness 109 between two End Housings 100, 101 housing one joint each. Referring now to **Figure 5B**, CMM Segments2, 4, 6 and 7 32, 34, 36 and 37 comprise a Double Housing 103 housing two joints, one at each end. Referring now to **Figure 5C**, CMM Segment8 38 comprises a Probe End

Housing 105 housing CMM Joint7 57 at one end with CMM Probe Mounting Means 39 at the other end - to which a Probe 90 is attached ending in Probe end 3.

Robot Exoskeleton joint and segment layout

The segments and joints of the Robot Exoskeleton 6 in the Robot CMM Arm 1 are named and laid out in general terms as follows.

Segment	Name	Location description	Comparative Length
Robot Segment 1	Base	Between base end and Joint 1	Short
Robot Segment 2	Shoulder	Between Joint 1 and Joint 2	Short
Robot Segment 3	Upper Arm	Between Joint 2 and Joint 3	Long
Robot Segment 4	Elbow	Between Joint 3 and Joint 4	Short
Robot Segment 5	Lower Arm	Between Joint 4 and Joint 5	Long
Robot Segment 6	Hand	Between Joint 5 and Joint 6	Short
Robot Segment 7	Wrist	Between Joint 6 and Joint 7	Short
Robot Segment 8	Probe	Extending from Joint 7	Short

Joint	Name	Type	Rotation	Brake
Robot Joint 1	Base	Axial	>360 degs	No brake
Robot Joint 2	Shoulder	Orthogonal	>180 degs	Brake
Robot Joint 3	Pre-elbow	Axial	>360 degs	Brake
Robot Joint 4	Elbow	Orthogonal	>180 degs	Brake
Robot Joint 5	Pre-wrist	Axial	>360 degs	Brake
Robot Joint 6	Wrist	Orthogonal	>180 degs	Brake
Robot Joint 7	Sensor	Axial	>360 degs	Brake

Each Robot Segment comprises one or more significant items:

Segment	Item	Joints	Description
Robot Segment 1	Base	1	Machined aircraft aluminium
Robot Segment 2	Shoulder	1,2	Machined aircraft aluminium
Robot Segment 3	Housing	2	Machined aircraft aluminium
	Link	0	Carbon fibre shape
	Housing	3	Machined aircraft aluminium
Robot Segment 4	Elbow	3,4	Machined aircraft aluminium
Robot Segment 5	Housing	4	Machined aircraft aluminium
	Link	0	Carbon fibre shape

	Housing	5	Machined aircraft aluminium
Robot Segment 6	Hand	5,6	Machined aircraft aluminium
Robot Segment 7	Wrist	6,7	Machined aircraft aluminium
CMM Segment 8	Probe	7	Machined aircraft aluminium

Base Layout

Referring now to **Figure 5D**, the Base 4 comprises CMM Segment1 31 housing CMM Joint 1 51 with Joint Centre 21 screwed into Mounting Plate 8 by means of a standard 3.5" by 8 heavy duty thread 116 and Robot Exoskeleton Segment1 41 housing Robot Joint1 61 with Joint Centre 21 rigidly attached to CMM Segment 1 31 with bolts 106. The Mounting Plate 8 is attached to the Surface 7 by Mounting means 104 such as Mounting Bolts 107. Both the Internal CMM Arm 5 and the Robot Exoskeleton 6 have base segments 31, 41 respectively. In this first embodiment, Robot Segment1 41 is rigidly attached to CMM Segment1 31 with counterbored bolts 106. Referring now to **Figure 5E**, in another embodiment of this Robot CMM Arm 1 invention, CMM Segment1 31 can be mounted to a first surface 7a and Robot Segment1 41 can be mounted to a second surface 7b in such a way that CMM Segment1 31 is not attached to Robot Segment1 41. Referring now to **Figure 5F**, in a further embodiment of this Robot CMM Arm 1 invention, both the CMM Segment1 31and the Robot Segment1 41 can be independently mounted to the same Surface 7. Referring now to **Figure 5G**, in a further embodiment of this Robot CMM Arm 1 invention, CMM Segment1 31 can be attached, rigidly or flexibly to Robot Segment1 41 which is mounted on a surface 7. Referring now to **Figure 5H**, in a further embodiment of this Robot CMM Arm invention, CMM Segment1 31 and Robot Segment1 41 can be the same base item 4 mounted on surface 7 to which both CMM Segment2 32 and Robot Segment2 42 are attached via CMM Joint1 51 and Robot Joint1 61 respectively. It is a purpose of this Robot CMM Arm invention that there can be any form of base mounting.

Robot CMM Arm Reach

This Robot CMM Arm 1 invention is provided in this first embodiment as a range of portable Robot CMM Arms with different reaches. The portable Robot CMM Arm Reach 80 varies from 0.6m to 3m. The scope of this invention is not limited to reaches within this range and the Reach 80 could be less than 0.6m or more than 3m.

Internal CMM Arm structure

Stiffness and mass

It is an object of this invention to minimise the mass of the Internal CMM Arm 5, which in turn allows the mass of a portable Robot CMM Arm 1 to be minimised because it requires less stiffness and motor power to move the Internal CMM Arm 5, thereby making the Robot CMM Arm 1 more portable. The Robot Exoskeleton 6 supports and drives the Internal CMM Arm 5 so as to minimise stresses on the

Internal CMM Arm 5 and in particular on the Internal CMM Arm Joints 51-57. By comparison, a Manual CMM Arm is designed for stresses applied to it by the operator, which are significantly higher than those on the Internal CMM Arm 5. This means that an Internal CMM Arm 5 does not need as high stiffness as a Manual CMM Arm of similar reach and is lighter than it.

Link Member diameter and thickness

The larger the Link Member diameter 108, the stiffer it is and the more accurate it is. With advances in materials science, the stiffness to weight ratio for arms is increasing as new stiffer and lighter materials become available. The Internal CMM Arm 5 has two long Link Members 102 in the upper arm and lower arm: CMM Segment3 33, CMM Segment5 35. The Link Member diameter 108 of the Internal CMM Arm 5 is 70mm. The scope of this Robot CMM Arm 1 invention is not constrained to this Link Member diameter; Link Member diameters more or less than 70 mm can be used. During handling by an operator, the forces and torques on a Manual CMM arm come from, amongst others: gravity which is related to the combination of joint angles at that instant in time, the compensating device, the accelerations, and the operator induced forces and torques. The operator can apply bending forces on either link. For this reason, a Manual CMM arm typically has the same link diameter for both segments. The Robot Exoskeleton 6 supports all segments 32-38 of the Internal CMM Arm 5 approximately equally. For this reason, the Internal CMM Arm 5 of this first embodiment has the same Link Member diameter 108 for both segments 33 and 35. The scope of this Robot CMM Arm invention is not constrained to a uniform Link Member diameter and Link Member diameters can be different.

The Link Member thickness 109 of the Internal CMM Arm is preferably 3mm for both segments 33 and 35. For longer reach arms, Link Member thickness 109 and/or the Link Member diameter 108 are typically increased to maintain stiffness. For shorter reach arms, the Link Member thickness 109 and /or the Link Member diameter 108 are typically reduced to save weight. The Link Member diameters and thicknesses are parameters that are optimised in the design process for different design specifications and manufacturing constraints.

Shape

The Robot Exoskeleton segments 42-48 must pass down over the Internal CMM Arm segments during assembly. The shape of the segments of the Internal CMM Arm 32-38 are constrained to have as small a maximum radial dimension as possible. Any reduction in maximum radial dimension enables the Robot Exoskeleton segments 42-48 to be reduced in size and this makes the Robot CMM Arm invention smaller and more flexible in its application.

Robot Exoskeleton structure

Performance

It is an object of this first embodiment that the Robot CMM Arm 1 is portable and that the weight be minimised. This object is not compatible with requirements of minimising cycle times and the correspondingly high angular accelerations at the joints. Performance in terms of maximum angular velocities and accelerations are higher for a short reach Robot CMM Arm 1 than for a long reach Robot CMM Arm 1. Maximum joint angular velocities are typically in the range 20 deg/sec to 400 deg/sec. RobotJoints1-4 61-64 have lower maximum angular velocities than RobotJoints 5-7 65-67 because the Torques are higher. In the case of a long Reach 80 of 3m and a Robot CMM Arm weight of below 30 kg, then Joint 2 can have a maximum angular velocity of 20 deg/sec. In the case of a short Reach 80 of less than 1m and a Robot CMM Arm weight of above 20 kg, then Joint 7 can have a maximum angular velocity of 400 deg/sec. The scope of this Robot CMM Arm invention is not constrained to this range of maximum angular velocities and the maximum angular velocity of a joint can be higher than 400 deg/sec or lower than 20 deg/sec.

Mass and stiffness

The Robot Exoskeleton structure is much less stiff than the Internal CMM Arm since high stiffness is not required for the functions of support and drive. The Robot Exoskeleton structure is therefore light, making the Robot CMM Arm more portable. There is a virtuous circle in that for given performance criteria, a reduced mass in any moving segment requires less powerful drive systems that in turn weigh less. Typical masses for a range of portable Robot CMM Arms vary from 18kg for a 1m Reach to 32 kg for a 3m Reach. The scope of this Robot CMM Arm invention is not constrained to this range of masses and the maximum mass can be higher than 3 kg or lower than 18 kg.

Shape

The Robot Exoskeleton structure is compact and lies close to the Internal CMM arm. This means that the Robot CMM Arm can access difficult areas for measurement such as car interiors. The Robot CMM Arm can thus be applied to applications that cannot be tackled without extensive preparation of the object such as when a car seat can not be measured in situ but must be first removed from the car. The Robot Exoskeleton Segments 42-48 form a sealed shape to protect the Internal CMM Arm Segments 32-38 from exposure to damaging solids, liquids or gases during use. The Robot Exoskeleton Segments 42-48 are hollow to fit over the Internal CMM Arm Segments 32-38. The Robot Exoskeleton shape also serves the functions of making the Robot CMM Arm manually usable and protects parts of the Internal CMM Arm in the event of a collision. Parts of the Robot Exoskeleton structure have non-functional surface shape for reasons of aesthetics. One of the largest factors determining the Robot Exoskeleton shape is the size and location of the motor and gearbox drive elements.

Materials

Internal CMM Arm materials

The Housings 100, 101, 103, 105 are made of aircraft aluminium; the aluminium is anodised. The Link members 102 comprise a thin-walled tube made of a woven carbon fibre composite material that provides a near-zero coefficient of thermal expansion, high stiffness and low density. Link members 102 can be attached to End Housings 100, 101 by an adhesive such as epoxy, whilst being supported in a precision jig as will be well understood by a person skilled in the art.

Robot Exoskeleton materials

The joint housing items are made of aircraft aluminium. The aluminium is anodised. The link items comprise a precision moulding of carbon-fibre. The link items are attached to joint housing items by an adhesive such as epoxy, whilst being supported in a precision jig.

Robot CMM Arm Mounting

It is an object of this invention that the Robot CMM Arm can be mounted onto a number of different structures in different orientations using a number of different mounting means to suit the application that it is used for.

Mounting means

Mounting the Robot CMM Arm 1 to a surface 7 can be by many means 104 including bolting down with bolts 107, magnetic mounting, vacuum mounting and clamping. It is important that the mounting means 104 used is stiff enough so as not to introduce movement between the mounting plate 8 and the surface 7 during operation of the Robot CMM Arm 1, thus rendering the Robot CMM Arm 1 less accurate.

Horizontal surfaces

Referring to **Figure 6**, the Robot CMM arm is normally mounted on the horizontal mounting surface 112 of a portable stand 110 using a standard 3.5"x8 thread 116. The stand 110 has three wheels 111 that can be locked. The stand 110 has retractable feet 113. The stand 110 has a large footprint to avoid it toppling over. The footprint is larger than for a corresponding Manual CMM Arm because the operator takes part of the arm load of a Manual CMM Arm through his feet which reduces the torque on the stand 110. The mass of the stand 110 is larger than for a corresponding Manual CMM Arm stand because the Robot CMM Arm 1 is heavier than a corresponding Manual CMM Arm. The stand 110 has an extensible vertical member 115 to raise or lower the base of the Robot CMM Arm. The stand 110 must be used on a stiff floor surface and not on a carpet or compressible floor covering material. The stand 110 will preferably be heavy so that the dynamics of the Robot CMM Arm do not cause it to rock; the control of a portable Robot CMM Arm mounted on a stand limits angular accelerations and velocities to avoid rocking the stand 110 and losing accuracy. An example of a stand 110 for short reach Robot

CMM Arms is stand number 231-0 weighing approximately 100kg and manufactured by Brun. Instrument Company (US) that is suitable for short and medium reaches. Long reach Robot CMM Arms require a larger and sturdier stand. Referring to **Figure 7A**, the Robot CMM Arm 1 can be rigidly mounted on a stable table 120 such as an optical bench or granite block that can be isolated from vibrations travelling through the floor 119 by vibration absorption means 121 situated above the supports 122. Referring to **Figure 7B**, the Robot CMM Arm 1 can be mounted directly to the floor 119. Referring to **Figure 7C**, the Robot CMM Arm 1 can be mounted onto a surface plate 123 mounted on the floor 119. Referring to the plan view of **Figure 7D**, the Robot CMM Arm 1 can be mounted on a rail axis 124 on which it travels across the floor 119. The Robot CMM Arm 1 is shown in three different positions A, B, C along rail axis 124. This means that the Robot CMM Arm 1 can measure a much larger volume of a large object 9. The rail axis 124 is preferably linear. The rail axis 124 is preferably mounted above the floor 119 such that it can be removed and reinstalled in a different location; alternatively, the rail axis 124 can be permanently embedded in the floor 119. The rail axis 124 can be manually driven, motor driven in response to manual actuation preferably via a button, or CNC driven. The Robot CMM Arm 1 will not be stable whilst translating along the rail axis 124. It is preferable that the Robot CMM Arm 1 does not measure whilst translating along the rail axis 124 and instead the rail axis 124 is used to move the Robot CMM Arm 1 from one measurement location to another such as from A to C via B. However, the Robot CMM Arm can measure during translation along the rail axis 124 but the accuracy will normally be reduced; this situation is most likely when the rail axis 124, is part of a large machine to which the Robot CMM Arm 1 is mounted.

Other orientations

For some applications, the Robot CMM Arm 1 is mounted in an orientation that is not a horizontal surface and in which the Robot CMM Arm 1 is not approximately vertically upright. Referring to **Figure 8A**, the Robot CMM Arm 1 is mounted orthogonal to a wall 125. Referring to **Figure 8B**, the Robot CMM Arm 1 is suspended from a gantry 126; alternatively it could be suspended form a ceiling. Referring to **Figure 8C**, the Robot CMM Arm 1 is mounted on a platform 127 with a surface at 60 degrees to the vertical. Referring to **Figures 8D and 8E**, the Robot CMM Arm 1 is mounted on a large, 3-axis conventional CMM such as are employed in automotive companies. There are many types of 3-axis conventional CMM including the Horizontal arm CMM 128 and the Moving bridge CMM 129. The Robot CMM Arm 1 has significant mass, it is typically expected to weigh from 18-32 kg depending on its accuracy and the reach of the arm, but it could weigh more or weigh less. For mounting on a conventional CMM, a light Robot CMM Arm based on this present invention could be designed with a mass substantially below 12 kg. For automotive applications in which the Robot CMM Arm 1 is mounted on a conventional CMM, as shown in Figure 8E, the Robot CMM Arm is preferably attached to a Moving bridge CMM 129 and suspended vertically downwards from the Vertical column 130 of the Bridge 131. In this mode, by a combination of the movement of the Moving Bridge CMM 129 and the

Robot CMM Arm 1 movement, the Robot CMM Arm 1 can access all parts of the object 9 being measured. The scope of this invention is not limited to the Robot CMM Arm 1 being mounted vertically downwards from the vertical column 130 of a bridge type conventional 3-axis CMM 131 with 3 linear axes or from the horizontal arm 132 of a Horizontal Arm CMM 128 also with 3 linear axes. The Robot CMM Arm 1 can be mounted from any substantial conventional CMM in any orientation with any number of axes. It is a purpose of this invention that the Robot CMM Arm 1 can be mounted at any orientation in free space from either a fixed or a movable structure.

Rigid and non-rigid mounting

The Robot CMM Arm 1 is preferably mounted to a surface 7 that is rigid with respect to the object 9 being measured. In some cases, there can be a continuous relative movement between the Robot CMM Arm 1 and the object 9 being measured such as caused by large machinery operating nearby that transmits vibrations through the floor. Or there can be an occasional relative movement between the Robot CMM Arm 1 and the object 9 being measured such as caused by a lorry driving by or an accidental knock to the object being measured. Or there can be slow relative movement between the Robot CMM Arm 1 and the object 9 being measured such as caused by thermal expansion of the structure on which the Robot CMM Arm and the object are mounted. Referring to **Figure 9**, that shows the case of relative movement between the base end 4 of the Robot CMM Arm 1 and the object 9 being measured by the Robot CMM Arm 1, the relative movement in 6 degrees of freedom can be measured by an independent measuring device. Examples of such an independent measuring device are the laser tracker by Leica and, preferably, a Photogrammetric tracker 140 by Krypton. The Robot CMM Arm 1 and the Photogrammetric tracker 140 are mounted on a surface plate 123. The object 9 is mounted on a floor 119 subject to movement such that there is significant relative movement between the object 9 and the surface plate 123. Photogrammetric targets 141 are attached to the object 9 such that a minimum of 3 targets and preferably more are visible to the Photogrammetric tracker 140 at any time during the measuring process. It is important that the Photogrammetric Tracker 140 measurements of the relative movement are synchronised in time with the Robot CMM Arm 1 measurements. Time synchronisation can be by any method commonly known to an expert in the trade including the triggering of measuring devices simultaneously, time stamping all measurements to a common clock for later processing. Such processing can include temporal interpolation when the relative movement measurement and the Robot CMM Arm measurement are not taken at the same instant. The process of calibrating the Photogrammetric Tracker 140 measurements to the Robot CMM Arm 1 measurements is well known to a person skilled I the trade. The result is measurements of Object 9 that are corrected for measured relative movement between the Robot CMM Arm 1 and the object 9.

Robot CMM Arm Range

The reach 80 of the Robot CMM Arm 1 depends on the application. The Robot CMM Arm 1 of this first embodiment is provided as a range of portable Robot CMM Arms 1 with different reaches 80. For exemplary reasons only, these reaches 80 might be from 0.5m to 5m with reaches 80 of 1m and 1.5m likely to be the most requested by component customers and reaches 80 of 2m to 3.5m to be those requested most by automotive assembly customers. The reach 80 of the Robot CMM Arm 1 invention is not constrained in this disclosure; Robot CMM Arm reach 80 can be longer or shorter than the ranges quoted. The use of the Robot Exoskeleton to support the Internal CMM Arm means that Robot CMM Arms can have longer reaches than the 2m effective limit of Manual CMM Arms. This means that applications requiring reaches longer than 2m (for which Manual CMM Arms are not practicably supplied) can be carried out by Robot CMM Arms. This first embodiment of a Robot CMM Arm 1 is a portable system and is not designed for high angular velocities and accelerations in order to limit the weight of the Robot CM Arm 1. Other embodiments of a Robot CMM Arm 1 can be designed for much higher angular velocities and accelerations. In order to keep the same drive system elements across the range of Robot CMM Arms 1, a lower maximum angular velocity for longer reaches is accepted in this first embodiment. The key difference across the range is a variety of lengths of the links 102. There can also be two or more ranges of portable Robot CMM Arm eg 0.6-1.2m and 1.5m-3m reach 80.

Robot CMM Arm System Overview

Referring now to **Figure 10**, the architecture of this first embodiment of the Robot CMM Arm System 150 is described. A Control Box 159 is mounted onto the Base 4 of the Robot CMM Arm 1. Power is supplied by means of a power cable 155 connected to a power connector 195. A power switch 156 and power LED 157 are provided. An interface connector 194 is provided for, amongst other things, connecting to a probe box 295 via a probe box to arm cable 296. A laptop 151 is connected by means of a Laptop communication cable 152 to laptop connector 197. A Pendant 153 is connected by means of a Pendant communication cable 154 to pendant connector 198. A network 200 is connected via network connector 199. Both the Pendant 153 and the laptop 151 can operate for a period from batteries 163, 164. The pendant battery 163 is recharged by placing the pendant in a recharge point 158 with electrical contacts 328; power connections are automatically made when the pendant is correctly placed in the recharge point. The laptop battery 164 is recharged from mains electricity. A touch trigger probe 92 makes automatic power connection 160 and trigger connection 161 when mounted on the Robot CMM Arm 1. An Optical probe 91 makes automatic power connection 160, trigger connection 161 and probe communications connection 162 when mounted on the Robot CMM Arm 1.

Referring now to **Figure 11**, the internal architecture of the Robot CMM Arm 1 is described. A Control PCB 172 is connected to ground line 165 and +5 Volt power rail 166. Seven motors 176, one driving each Robot Exoskeleton Joint, are connected to seven amplifiers 175 by motor cables 196 and are driven

from seven +/- 10V control signals 168 output from the Control PCB 172 to the amplifiers 175. The Control PCB 172 is connected to seven Joint PCBs 173 by a serial bus 169. The Control PCB 172 has two further communication connections 152 and 154 for communicating with the laptop 151 and the pendant 153 respectively. A +24 Volt power rail 167 provides power to the amplifiers 175. A power supply unit 171 is connected to a power supply cable 155, a battery 170, ground 165 and power rails 166, 167. At least one Joint PCB 173 is connected to a probe 90 with power 160, trigger 161 and, where applicable, communications 162. All seven motors 176 have brakes 177 which are driven by signals from the Joint PCBs 173. The Internal CMM arm 5 comprises seven CMM encoders 178 attached to the joint PCB 173. Seven encoders 179 mounted on the seven motors 176 driving the Robot Exoskeleton 6 are attached to the joint PCB 173. A thermocouple 180 mounted on the Internal CMM Arm 5 is connected to each Joint PCB 173. A strain gauge 181 mounted on the Internal CMM Arm 5 is attached to each Joint PCB 173. Two limit switches 182 are connected to each Joint PCB 182. Two operator Buttons 183 are connected to the Joint PCB 173 of the 7th joint. Touch sensors 184 are connected to each Joint PCB 173. Each Joint PCB 173 is connected to ground line 165 and +5 Volt power rail 166. A trigger bus 174 is connected to each Joint PCB 173 and the Control PCB 172; it is used for latching the seven CMM encoders 178.

The scope of this invention is not limited to the architecture of the Robot CMM Arm System 150 disclosed in this first embodiment but includes all architectures that have the technical effect of the Robot CMM Arm System 150. For instance, in a further embodiment, the Control Box 159 is separate from the Robot CMM Arm 1 and connected to the base 4 of the Robot CMM Arm with a cable. This architecture can be necessary for Robot CMM Arms where the items in the Control Box 159 require the Control Box 159 to be too big to sensibly fit at the base 4 if the Robot CMM Arm is to be portable. The architecture of the first embodiment is preferred because the portable Robot CMM Arm is a single unit without the increased manufacturing cost and location footprint of a separate control box 159. In an additional embodiment, a full size personal computer is used instead of a laptop 151 and the Control PCB 172 is mounted in the personal computer on a standard bus such as the PCI bus; alternatively a network of several personal computers are used. In a further embodiment, the pendant is not supplied and the laptop 151 is used to control the Robot CMM Arm 1.

Internal CMM Arm encoders

The Internal CMM Arm 5 comprises angular encoders 178 at each CMM joint 51-57. The scope of this invention is not limited to angular encoders or to any particular design of angular encoders but can utilise any accurate form of angle measuring device. The resolution and accuracy of an angular encoder is limited by the diameter of the encoder that in turn limits the number of edges that can be present on the angular encoder. In general, in a range of angular encoders, those angular encoders with a higher resolution are more accurate. In order to optimise the accuracy of the Robot CMM Arm 1 it is desirable

to have more accurate angular encoders towards the base end 2 than towards the tip end 3 of the Internal CMM Arm 5. This is because a small rotation at a base end joint such as 21, 22 will cause a big movement at the tip end 3. Whereas a small rotation at a tip end 3 joint such as 25, 26 or 27, will cause a small movement at the tip end 3. The movement at the tip end for a given joint rotation, is proportional to the distance of the joint from the tip end 3, if all other factors are controlled. The Internal CMM Arm 5 uses CMM encoders 178. The CMM joints 21, 22 towards the base end 2 of the Internal CMM arm 5 have larger diameter encoders because at full stretch there is a longer distance from the CMM encoder 178 to the probe end 3. The remaining joints 23-27 at the elbow and wrist of the Internal CMM Arm 5 have smaller diameter encoders because there is a small to medium distance from the encoder 178 to the probe end 3. These smaller encoder diameters reduce the weight of the arm carried by the operator at full stretch, make it compact and easy to handle. In the case where there is a large virtual reach 81 caused by the optical probe 91, it can be important to have higher resolution encoders at the joints 23-27 towards the probe end of the arm. It is expected that the technology behind angular encoders will improve and angular encoders with a given accuracy will reduce in diameter and weight. Referring now to **Figure 12**, an Internal CMM Arm encoder 178 comprises Renishaw RESR Angular encoders 185 with a 20 micron scale pitch are used together with one Renishaw RGH20 readhead 186 per joint. A 52mm diameter RESR with 8192 counts is used on each of CMM Joints 23-27 providing a quoted accuracy of +/- 5.6 arcseconds per joint. A 150mm diameter RESR with 23,600 counts is used on each of CMM Joints 21 and 22 providing a quoted accuracy of +/- 1.9 arcseconds per joint. The output of a Renishaw readhead 186 goes to a Renishaw RGE interpolator 187. The output from each Renishaw interpolator 187 feeds into the Joint PCB 173.

<u>Robot Exoskeleton drive system structure</u>

Environmental emissions

It is a purpose of this invention that the portable Robot CMM Arm operates quietly and can be used in office environments. It is important that the level of emitted audible noise is kept to a minimum in the design. Inherently low-noise drive systems including motors and gearing methods are selected to minimise the emission of audible noise. Fundamentally, the level of audible noise output increases with the velocities and accelerations at which the Robot CMM Arm is driven. Reducing the velocities and accelerations has little impact on cycle time in many applications. This is because typically 90% of the cycle time is taken up with measuring which is a slow process and only 10% can be reduced by means of increasing speed. Where minimising the level of emitted audible noise is a key usage criteria, the control system can be set by the user to scan quietly with low velocities and accelerations. The Robot CMM Arm minimises the emission of electromagnetic radiation by incorporating drive system components with low electromagnetic radiation and providing shielding around the components emitting the most electromagnetic radiation.

Heat transfer

It is an object of this invention that the heat transfer to the Internal CMM Arm 5 from the motors 176 and other drive components in the Robot Exoskeleton 6 is minimised, resulting in the Internal CMM Arm 5 being more accurate due to a comparatively stable and uniform temperature. It is disclosed that:

- there are no direct heat conductive links of significance from the Robot Exoskeleton motors 176 to the Internal CMM Arm 5 to eliminate heat transfer by conduction; the transmission means 10 are small and their materials have a low coefficient of thermal conductivity; none of the hot items in the control box 159 are directly attached to the base 4 of the Robot CMM Arm; that means there is no conduction between the hot items in the control box 159 and the base 4 of the Robot CMM Arm;
- the Internal CMM Arm segments 32-38 are coated to minimise heat transfer by radiation to the Internal CMM Arm 5 from the motors 176;
- the motors are well ventilated and provided with heat sinks to maximise heat transfer by convection and minimise their operating temperatures; the angular velocities of the joints during operation are programmed to avoid the motors 176 overheating;
- referring now to **Figure 13**, there is a duct 189 between the Internal CMM Arm segments 32-38 and the Robot Exoskeleton segments 42-48; a low-capacity fan 190 with a large filter 191 situated in the base 4 sucks in air 192 and blows it along the duct 189 between the Internal CMM Arm 5 and the Robot Exoskeleton 6; the majority of the air 192 exits at the tip end 3 between Internal CMM Arm segment 38 and Robot Exoskeleton segment 48. This forced circulation of air provides efficient cooling by convection. The fan 190 is selected to run quietly in an office environment. The filter 191 is large and fie; in operation in an office environment, the filter 191 should not need replacement or cleaning for 5 years. Part of the air 192 sucked in by the fan 190 passes through the control box 159 and exits through the vent 353 in the control box; this air circulation removes heat from the control items including the control PCB 172, the PSU 171 and the amplifiers 175.

Robot Exoskeleton drive systems

The Robot CMM Arm 1 is driven by electric motors 176 that are brushed DC servo motors with encoders. The drive systems in this invention are not limited to electric motors of any kind, but can be driven by a range of different power systems including hydraulics or pneumatics. Hydraulics and pneumatics can introduce less vibration into the Robot CMM Arm than electric motors with encoders. Electric motors 176 can be AC or DC servo motors, stepper motors or other forms of motor; the motors 176 can be brushed or brushless. To reduce manufacturing cost, reduce the wieght of the Robot CMM Arm and to produce a more compact design, the CMM encoders 178 can be used for position feedback; the Robot exoskeleton encoders 179 are not then required. To further reduce manufacturing cost, stepper motors can be used in an open loop format without any position sensing in the loop. Some

applications require only low accelerations of the Robot CMM Arm and require less powerful [illegible]e systems. Other applications require high accelerations and require more powerful drive systems. Applications on a car production line require sturdy Robot CMM Arms 1 that can survive an impact with a car body. Due to the presence of the Internal CMM Arm 5, for most applications it is not essential to have low backlash in the drive train elements. Low cost and low mass drive train components such as belt drives can be used. In this embodiment, one motor 176 is used to drive each joint 61-67.

Transmission means

In this first embodiment, the base 41 of the Robot Exoskeleton 6 is rigidly attached to the base 31 of the Internal CMM Arm 5 such that there can be no significant relative movement between the two bases 41 and 31 and that forces and torques are transmitted through this rigid attachment. Furthermore, seven transmission means 72-78 are provided, one for each joint 21-27. Each of the transmission means 72-78 is in physical contact with the corresponding segment 42-48 of the Robot Exoskeleton 6 and the corresponding segment 32-38 of the Internal CMM Arm 5. During operation, the centres and axes of the CMM Joints 51-57 and the Joints 61-67 are in substantially the same positions. Factors resulting in slight misalignments of these joint centres and axes include:

- different strains of the Internal CMM Arm segments 32-38 compared to the Robot Exoskeleton segments 42-48
- elastic deformation of the transmission means 72-78; in this first embodiment, all of the transmission means 72-78 comprise an elastic means and do not rigidly attach the Internal CMM Arm 5 and the Robot Exoskeleton 6

In this first embodiment, the only rigid attachment between the Internal CMM Arm 5 and the Robot Exoskeleton 6 is at the base end 2; in particular, there is no rigid attachment between the Internal CMM Arm 5 and the Robot Exoskeleton 6 at the probe end 3.

The transmission means 72-78 are approximately centred at the Centres of Gravity CG2-CG8 of the corresponding CMM Segments2-8 32-38. Referring now to **Figure 14**, the Robot CMM Arm 1 is shown static in the horizontal position from Joint 2 onwards. Arrows are shown in the direction of the gravitational force from the centres of gravity CG3-CG8 of CMM Segments2-8 32-38. These arrows pass through the centres of the transmission means 73-78.

Referring now to **Figure 15**, CMM Segment8 38 and standard probe 90 rigidly mounted to CMM Segment8 38 are supported by Transmission Means8 78 at Centre of Gravity CG8 such that there are negligible resultant forces or torques on CMM Joint7 57. Centre of Gravity CG8 is the centre of gravity of CMM Segment8 38 combined with standard probe 90 rigidly mounted to CMM Segment8 38. This is a desirable state since one of the objects of this Robot CMM Arm 1 invention is to maximise accuracy

by reducing forces and torques on the joints of the Internal CMM Arm 5. In practice, probes 90 including optical probes 91 of various masses, centre of gravity positions and inertias will be attached to the probe end 2 of the Robot CMM Arm 1. In an ideal situation, all probes 90 will be designed such that when mounted on CMM Segment 38, the position of the Centre of Gravity of the combined probe 90 and CMM Segment8 38 is centred on the axis of CMM Segment 38 in the centre of the Transmission Means8 78. In this way, attaching a probe 90 of high mass centred on Centre of Gravity CG8 will not reduce the accuracy of the Robot CMM Arm because the extra mass is fully supported by the Robot Exoskeleton 6 via the Transmission Means8 78.

Referring now to **Figure 16**, CMM Segment7 37 is supported by Transmission Means 77 at its Centre of Gravity CG7. There are negligible transmitted forces or torques through CMM Joint7 57. Thus there are negligible resultant forces or torques on CMM Joint6 56. In the case of CMM Joint1 51 there is a downward force on it equivalent to the weight of CMM Segment2 32. It will be well understood by those skilled in the art that in the same way the forces and torques on CMM Joint2-5 52-55 are also negligible for the static horizontal condition of Figures 14-16.

Each Transmission Means 10 transmits a drive. In the case of axial joints, the drive is a torsional drive; the Robot Exoskeleton segment rotates axially, providing a torsional drive through the Transmission Means onto the Internal CMM Arm segment. In the case of orthogonal joints, the drive is a radial drive; the Robot Exoskeleton segment rotates orthogonally, providing a radial drive through the Transmission Means onto the Internal CMM Arm segment.

Transmission Means	**Drive**
TransmissionMeans2	Torsional
TransmissionMeans3	Radial
TransmissionMeans4	Torsional
TransmissionMeans5	Radial
TransmissionMeans6	Torsional
TransmissionMeans7	Radial
TransmissionMeans8	Torsional

Referring now to **Figure 17**, the principle of the Transmission Means3 73 is shown in Longitudinal Section AA and Axial Section BB. The drive transmission of Transmission Means3 73 is radial. CMM Segment3 33 is moved by means of radial forces through Transmission Means3 73 from Robot Segment3 43. The Transmission Means3 73 comprises three Transmission Blocks 201 at 120 degree spacing rigidly attached to the inside of Robot Segment3 43; the Transmission Blocks 201 are made from a light material such as Aluminium. Bonded to the inner surface of the three Transmission Blocks

201 are two layers: an elastic material layer 203 such as neoprene and a low-friction material layer 2 such as PTFE that contacts with CMM Segment3 33. The Transmission Means3 73 do not transmit torsional or axial forces because the low-friction material layer 202 permits slip between the CMM Segment3 33 and the Robot Segment3 43 in the torsional and axial modes. The elastic material layer 203 is in constant compression when the Transmission Means3 73 is assembled in position. The elastic material layer 203 has a combined cross-sectional area, thickness and stiffness that enables it to remain within its design elastic range without rapidly increasing in stiffness during normal use or compressing a significant distance. A benefit from the use of low-friction material 202 is that heat is not generated through friction; this means that the drive power is reduced and the accuracy of the Internal CMM Arm 5 is maintained by eliminating thermal distortion due to frictional 'hot' spots. Transmission Means5 75 and Transmission Means7 77 are similarly arranged for radial drive transmission.

Referring now to **Figure 18,** the principle of the Transmission Means4 74 is shown in Longitudinal Section AA and Axial Section BB. The drive transmission of Transmission Means4 74 is torsional. CMM Segment4 34 is rotated by means of a torque through Transmission Means4 74 from Robot Segment4 44. The Transmission Means4 74 comprises a Collar 204 bonded to CMM Segment4 34. The Collar 204 further comprises three Driven flanges 209 spaced at 120 degrees, extending outwards radially and extending longitudinally. Three Slotted Transmission Blocks 205 at 120 degree spacing drive the driven flange. Each Slotted Transmission Block 205 comprises two pads of elastic material 203 bonded to the two drive faces of the slot of the Slotted Transmission Blocks 205. The Slotted Transmission Blocks 205 are attached to Robot Segment4 44 with bolts 206 using washers 207. The Slotted Transmission Blocks 205, the collar 204 and the washers 207 are made from a light material such as Aluminium. The elastic material 203 has an external low-friction material layer 202 such as PTFE that contacts with the Driven flanges 209. The Transmission Means4 74 do not transmit axial forces because the low-friction material layer 202 permits some slip between the CMM Segment4 34 and the Robot Segment4 44 in the axial mode. The Transmission Means4 74 partially transmits radial forces because although the low-friction material layer 202 permits some slip between the CMM Segment4 34 and the Robot Segment4 44 in the radial mode, the Driven flanges 209 are situated at 120 degrees and react together to provide a correcting force to any radial movement between the CMM Segment4 34 and the Robot Segment4 44. The elastic material layer 203 is in constant compression when the Transmission Means4 74 is assembled in position. The elastic material layer 203 has a combined cross-sectional area, thickness and stiffness that enables it to remain within its design elastic range without rapidly increasing in stiffness during normal use or compressing a significant distance. Transmission Means2 72, Transmission Means6 76 and Transmission Means8 78 are similarly arranged for torsional drive transmission.

It will be appreciated by an expert skilled in the field, that the Robot Exoskeleton 6 can transmit forces and torques to the Internal CMM Arm 5 using a wide range of transmission means 10 that all achieve the objective of minimising forces and torques on the Internal CMM Arm 5 so as to maximise the accuracy of the Robot CMM Arm 1. This Robot CMM Arm 1 invention provides for all transmission means 10 of transmitting forces and torques to an Internal CMM Arm 5 from a Robot Exoskeleton 6 such that the Robot CMM Arm 1 is automatically driven and accurate. For example, in alternative embodiments, the number of transmission means 10 can be more or less than seven. In further embodiments, transmission means 10 can rigidly attach the Internal CMM Arm 5 and the Robot Exoskeleton 6 at one or more locations such that forces and torques transmitted to the Internal CMM Arm 5 from the Robot Exoskeleton 6 do not affect the accuracy of the Robot CMM Arm 1. It will be further appreciated by an expert skilled in the field, that future apparatus arriving in the marketplace can appear to have a combined Internal CMM Arm and Robot Exoskeleton and can be claimed to be a conventional robot rather than a Robot CMM Arm. If such future apparatus has the technical effect of reducing the forces and torques on the CMM bearings and segments, then it will infringe this patent.

Robot CMM Arm Counterbalancing

Counterbalancing in Internal CMM Arm

If a counterbalance were employed in the Internal CMM Arm 5, the stress increases in the joint through which it acts and can also induce bending moments, both of which either cause reduced accuracy or require increase weight to counteract. The joints of the Internal CMM Arm 5 of the Robot CMM Arm 1 invention will typically be used for more cycles than a Manual CMM Arm because the Robot CMM Arm can be used up to 24 hours a day, 365 days a year less maintenance periods and shutdowns. If a joint has a high stress and is used continuously, then the counterbalance will generate more heat and the temperature of that joint in the arm will be higher than compared to low usage. This potentially increases error and can not be possible to compensate for. The bearings on that joint of the Internal CMM Arm 5 need to be designed to be stiff for a much larger number of lifetime cycles. Loose bearings are a significant cause for inaccuracy in the Internal CMM Arm 5 and cannot be compensated for. It is a purpose of this invention that the Robot Exoskeleton 6 carries the Internal CMM Arm 5 in such a way as to be an external compensating device. This external compensation minimises most of the forces and torques on the Internal CMM Arm 5 during motion and removes the benefits of an internal counterbalance. This means that the Internal CMM Arm 5 does not need a counterbalance and the Robot CMM Arm 1 will be lighter, simpler and cost less to manufacture without a counterbalance.

Robot Exoskeleton Counterbalance

The Robot CMM Arm 1 can be mounted with its base 4 in any orientation. In base orientations that are either vertically upwards or downwards, the Robot Exoskeleton 6 preferably has a counterbalance in Robot Joint2 62 that compensates for the weight of both the Robot Exoskeleton 6 and the Internal CMM

Arm 5. A counterbalance is a device that does not directly consume power from a power source such as electrical voltage, pneumatic or hydraulic pressures. This means that the drive system in Robot Joint2 62 can be less powerful, weigh less and consume less electricity.

Referring now to **Figure 19**, the base 4 of the Robot CMM Arm 1 is mounted vertically upwards and the direction of application A of the Counterbalance 210 is to lift RobotSegment3 43 of the Robot Exoskeleton 6 upwards against gravity towards a vertical position. The Counterbalance 210 is situated at one end of the axis of Robot Joint2 62. With the base 4 of the Robot CMM Arm 1 mounted vertically downwards, for example when hanging down from the column of a moving bridge 3-axis CMM 129, the direction of application of the Counterbalance 210 is to lift RobotSegment3 43 of the Robot Exoskeleton 6 upwards against gravity towards a horizontal position. Preferably a single Counterbalance 210 acts to provide a torque through Robot Joint2 62. The Counterbalance 210 is preferably a coil spring. The Counterbalance 210 is set to the optimum value to minimise the maximum torque required to rotate Robot Joint2 62 in any orientation of Robot Joint2 62. This Counterbalance 210 means that a smaller and lighter drive system can be provided to drive Robot Joint2 62. In ideal circumstances, the Counterbalance 210 should act directly through the centre of Robot Joint2 62 to avoid applying bending moments to Robot Joint2 62. In this Robot CMM Arm invention, CMM Joint 2 of the Internal CMM Arm 5 is situated in the middle of Robot Joint2 62. The Counterbalance 210 is therefore situated off-centre and applies a bending moment to Robot Joint2 62. The structure of the Robot Exoskeleton 6 and in particularly the components around Robot Joint2 62 is stiff enough to counteract the bending moment from the Counterbalance 210 and keep the bending of the Robot Exoskeleton 6 within desired limits. The direction of the torque compensation of the Robot Joint2 62 is the opposite for either vertically upward or vertically downward Robot CMM Arm base 4 orientation. The Counterbalance 210 provided can be turned so as to apply its torque in the opposite direction when the base 4 orientation of the Robot CMM Arm 1 changes direction. In a further embodiment of this invention, the Counterbalance 210 further comprises a Damper 211.

In an alternative embodiment, a selection of two Counterbalances 210 are provided for the arm, the first for application when the Robot CMM Arm 1 has a vertically upwards base 4 orientation and the second for application when the Robot CMM Arm 1 has a vertically downwards base 4 orientation; the appropriate Counterbalance 210 is fitted for the orientation of the base 4 of the Robot CMM Arm 1. In a further embodiment, a Counterbalance 210 with manual setting for the two different orientations is provided that is set up manually during installation of the Robot CMM Arm 1. In a further embodiment, a Counterbalance 210 that automatically adjusts to the orientation of the arm and provides the ideal compensation profile is employed. In an alternative embodiment of this invention, two Counterbalances 210 are provided situated on either side of Robot Joint2 62 and set to approximately the same torque, such that the bending moment across Robot Joint2 62 is negligible.

In other base orientations such as with the base of the Robot CMM arm mounted horizontally, for example when mounted on a wall, it is preferable not to have a Counterbalance 210 at Joint 2, unless the application is constrained such that it can be useful. In an alternative embodiment, this Robot CMM Arm invention can function without any Counterbalance 210 in the Robot Exoskeleton 6.

Joint limits

This first embodiment of the Robot CMM Arm 1 invention has hard limits to the rotation of each joint. A hard joint limit is a physical stop beyond which the joint will not rotate in the direction of the hard joint limit. These hard limits enable cables to be routed up the arm without the need for passing signals through infinitely rotating axial joints on contact rings. The cables simply coil or bend in the region of each joint in ways known to those skilled in the trade including cable-coiling areas.

With programmed actuation of this first embodiment of a Robot CMM Arm 1, the joint limits do not restrict the capabilities of the Robot CMM Arm 1 in any significant way. With manual actuation of a Robot CMM Arm 1 it can be that the operator loses track in his mind of where an axial joint is relative to its limits and hits a hard limit when he does not want to. Getting out of this undesirable situation usually requires a rotation of that joint by 360 degs in the opposite direction, which can involve rotating other joints simultaneously to avoid a collision.

Internal CMM Joint hard limits

In this first embodiment, there are no built-in hard joint limits in the Internal CMM Arm 5. The inherent orthogonal joint limits are all slightly in excess of the hard joint limits of the Robot Exoskeleton 6 such that the Robot Exoskeleton cannot force the Internal CMM Arm 5 onto a hard joint limit in normal operation. Simple rubber stops are located to avoid damage during assembly when the Internal CMM Arm 5 is unsupported by the Robot Exoskeleton 6. These rubber stops are not used in operation once the Robot CMM Arm 1 has been built.

Robot Exoskeleton Joint limits

In this first embodiment, each Robot Joint1-7 61-67 has first and second hard joint limits. Each hard joint limit is preferably a mechanical stop with a shock absorber element made of rubber attached to at least one impact side to soften any impact. For larger sizes of the Robot CMM Arm 1 invention, in which an impact involving an orthogonal joint could be considerable, the impact energy force is dissipated by axially compressing a partially pre-crumpled tube so situated as to absorb the impact. Pre-crumpling removes the initially high shock stress of impact onto a rigid body. After impact, the tube is simply replaced. The tube is preferably 100 mm long, made of pure aluminium, with 7mm in diameter and 1.5mm wall thickness and pre-compressed by 5% within a 9.5mm diameter jig, so as to fit within a 10mm bore in an orthogonal joint of a Robot CMM Arm 1. Adjustments are made to these

specifications for different size Robot CMM Arms with different quantities of impact energy to ab... It will be appreciated that any other appropriate way of absorbing impact energy through plastic deformation or other mode could equally be used, such as by shearing rather than crumpling a material. In this first embodiment, each Robot Joint1-7 61-67 has first and second soft joint limits. Each soft joint limit is preferably a limit switch 182.

Optimum Base orientation direction

The base 4 of the Robot CMM Arm 1 preferably has an optimum orientation direction marked on it. The base optimum orientation direction is the direction in which the base 4 should be oriented towards the centre of the working area in which the Robot CMM Arm invention is to be used. In the optimum orientation, Robot Joint1 61 can be rotated by equal amounts to either side before hitting hard limits.

Robot Joint 1 limits

In this first embodiment, Robot Joint1 61 is an axial joint. Referring to **Figure 20**, the total angular rotation of Robot Joint1 61 between the first and second physical joint limits is 630 degrees. The Robot Joint1 61 first hard joint limit pair 222A, 222B and second hard joint limit pair 223A, 223B are set at equal angles of 315 degrees to the base optimum orientation direction 221. The hard joint limits 222A and 223A rotate with Robot Segment2 42. The hard joint limits 222B and 223B remain static with Robot Segment1 41. The hard joint limits 222B and 223B each have a rubber shock absorber element 224 attached to the impact face. Two soft joint limit switches 182 are positioned so that the limit switch is contacted just before the joint reaches it hard limit. In a further embodiment, provision is made for the rotating hard joint limits 222A and 223A to be moved by the operator relative to Robot Segment2 42 to give an alternative total angular rotation of Robot Joint1 61 of 390 degrees. In alternative embodiments, the angular rotation of Robot Joint1 61 could be more than 630 degrees or could be less than 630 degrees. There could also be a plurality of joint limit settings up to a maximum total angular rotation. Similar hard joint limit means are provided for Robot Joints3,5,7 63, 65, 67. Similar soft joint limit switches 182 are provided for Robot Joints2-7 62-67.

Robot Joint 2 limits

In this first embodiment, Robot Joint2 62 is an orthogonal joint. Referring to **Figures 21A, 21B**, the angular rotation of Robot Joint2 62 is preferably 185 degrees. Referring to Figure 21B, the Robot Joint2 62 rotation starts with Robot Segment3 43 at 5 degrees past vertically upwards and first hard joint limit pair 225A, 225B touching through rubber pad 224. Referring to Figure 21A, the Robot Joint2 62 rotation finishes with Robot Segment3 43 vertically downwards and second hard joint limit pair 226A, 226B touching through rubber pad 224. When the Robot CMM Arm base 4 is oriented vertically upwards, the Compensator 210 on Robot Joint2 62 acts to rotate Robot Segment3 43 upwards towards the first hard joint limit pair 225A, 225B. When the Robot CMM Arm base is oriented vertically

downwards (not shown in Figures 21A, 21B), the Compensator 210 on Robot Joint2 62 is reversed in direction of action and acts to rotate Robot Segment3 43 towards the second hard joint limit pair 226A, 226B. Similar hard joint limit means are provided for Robot Joints4,6 64, 66.

Joint Brakes

This Robot CMM Arm 1 invention is not supported against gravity by an operator. If the power to the drive systems is cut, then without brakes 177, the Robot CMM Arm 1 will fall under gravity and can be damaged or damage one or more people or objects. In this first embodiment, all the Robot Joints1-7 61-67 have fail-safe brakes 177 that automatically apply in the event of a power cut. In this way, all the Robot Joints1-7 61-67are locked in the event of a power cut and this locking will work at any base mount orientation and any robot arm spatial layout. In an alternative embodiment, in which the Robot CMM Arm 1 should only be mounted with its base vertically upwards or vertically downwards, Robot Joint1 61 does not have a brake 177. In this case Robot Joint1 61 has a constant orientation and the effect of gravity will not cause acceleration of Robot Joint1 61.

Joint Bearings

Low friction bearings are used in the CMM Joints1-7 51-57 of the Internal CMM Arm 5 to minimise the amount that the Internal CMM Arm 5 warms up, especially with heavy-duty cycles. The stress on the bearings in the Internal CMM Arm 5 is typically less than for a Manual CMM Arm because most of the weight of the arm is compensated for by the Robot Exoskeleton. Referring now to **Figure 22**, pre-stressed taper roller bearings 230 are provided in CMM Joint3 53 an axial joint and CMM Joint4 54 an orthogonal joint. The taper roller bearings 230 provide high stiffness and compactness. The taper roller bearings 230 are pre-stressed by applying a pre-determined torque to a nut 231. The bearings 230 are fitted into housings 100 and 103 using an interference fit, performed using a thermal shrink-fit process in which the bearings are first cooled to –45C before insertion and result in a strong interference fit at room temperature. In a similar arrangement, pre-stressed taper roller bearings 230 are provided in each CMM Joint1-7 51-57. There are many ways of providing bearing arrangements in this invention. The scope of this invention is not limited to the use of pre-stressed taper roller bearings with thermal interference shrink-fits. Any type of bearings and methods of fitting and adjusting bearings can be used that satisfies at least the requirements of low weight, low friction and high stiffness.

Impact protection

The Robot CMM Arm 1 is portable. It is expected that it will suffer impacts during operation, mounting, dismounting and transport. Protruding aspects of the shape of the Robot CMM Arm 1 have bump pads made of plastic attached to them to absorb knocks. During operation, the axis following errors are monitored to minimise damage from impact by stopping motion on impact. A rigid case with foam inside is provided for transport in which the Robot CMM Arm 1 is completely surrounded by foam

shaped to the shape of the Robot CMM Arm 1 that supports it over a large proportion of its surface. The rigid case is preferably a flight case with wheels and lifting handles built into the casing. The Robot CMM Arm 1 is first moved by the control PCB 172 to a specially designated spatial orientation for transport before being powered down during which the brakes 177 actuate. During handling, the brakes 177 on the motors 176 are active; this makes the Robot CMM Arm 1 a rigid device; this makes it easy to handle the Robot CMM Arm 1 since parts of the Robot CMM Arm 1 do not rotate whilst handling.

<u>Probes and Tools</u>

Mounting

The Robot CMM Arm 1 has a base end 2 and a probe end 3. It can comprise one or more measuring probes 90 or tools 98 preferably mounted at its probe end 3 after CMM Joint7 57. A measuring probe 90 can be manually removed or automatically removed. Automatic removal is preferably by means of a probe change system such as a rack with locations for two or more probes 90.

Referring now to **Figure 23**, in this first embodiment, probe mounting means 240 are provided at the probe end 3 of the Robot CMM Arm 1 invention after CMM Joint7 57 for attaching up to two probes 90 employing two of three probe mounting means 240: first probe mounting means 244, second probe mounting means 247 and third probe mounting means 251. The first probe mounting means 244 comprises a M8x1.5 female thread 241 from a first mounting face 242 and an electrical contact means 243. The second probe mounting means 247 comprises a M20 male thread 245 from a second mounting face 246. The third probe mounting means 251 comprises a M30 female thread 248 and a third mounting face 250 with three precision grooves 249 at 120 degree intervals; a recessed probe connector 255 is situated in third mounting face 250. An additional recessed probe connector 258 is situated on CMM Segment8 38 for connecting a probe 90 when the recessed probe connector 255 cannot be used; connectors 255 and 258 are mechanically and electrically identical.

Referring now to **Figure 24**, a Renishaw TP20 probe body 93 is mounted on CMM Segment8 38 using first probe mounting means 244 by screwing it into thread 241 until it meets first mounting face 242; electrical contact is made between the Renishaw TP20 probe body 93 and the electrical contact means 243. A Renishaw TP20 probe module 94 is mounted on the Renishaw TP20 probe body 93 using the magnetic kinematic mount.

Referring now to **Figure 25**, a solid contact probe 95 is mounted on CMM Segment8 38 using second probe mounting means 247 by screwing it onto thread 245 until it meets second mounting face 246. To mount the solid contact probe 95, it is not necessary to remove the Renishaw TP20 probe body 93, but it is necessary to first lift off the Renishaw TP20 probe module 94 at the magnetic kinematic mount. This means that it is not necessary to recalibrate the Robot CMM Arm 1 with the Renishaw TP20 probe body

93 on each removal of the solid contact probe 95. An Optical probe 91 mounted on a bracket 253 with three cylinders 252 located at 120 degree intervals is mounted on third probe mounting means 251 after passing it over solid contact probe 95 over which bracket 253 has clearance by means of a larger internal diameter than the solid contact probe 95 external diameter. This means that the Optical probe 91 can be removed without first removing the solid contact probe 95 and has the advantage that it is not necessary to recalibrate the Robot CMM Arm 1 with the solid contact probe 95 on each removal of the Optical probe 91. In a similar way, the solid contact probe 95 or the Renishaw TP20 probe body 93 can be removed without realigning the Optical probe 91. The Optical Probe 91 has a centre of gravity 96 that is offset by distance 'd' from the axis of CMM Segment8 38. An example of an Optical probe 91 is a ModelMaker X70 from 3D Scanners (UK). Referring now to **Figure 26**, the bracket 253 has a bracket connector 256 with a cable 257 connecting the bracket connector 256 and the Optical probe 91. The three cylinders 252 of bracket 253 locate in precision grooves 249 and are held in place by nut 254 which screws onto thread 248. Bracket connector 256 automatically locates into recessed probe connector 255 as the cylinders 252 of bracket 253 locate in precision grooves 249 and is held in place by the nut 254. The location of the bracket 253 and hence the Optical probe 91 is repeatable in position and orientation relative to CMM Segment8 38 to an accuracy of the order of 0.025 to 0.05 mm (+/- 2 Sigma). The bracket can be positioned in three different orientations at 120 degrees intervals, but only one preferred position makes an automatic connection with the recessed probe connector 255. In a further embodiment, two or more sets of three precision grooves 249 are provided in face 250. This means that with two sets of three precision grooves 249, the bracket 253 can be oriented in six different orientations at 60 degrees intervals.

In this first embodiment, each probe's 90 centre of gravity preferably lies approximately on the axis of CMM Segment8 38 to minimise the effort to rotate the CMM Joint7 57 and to minimise any bending moments on CMM Joint7 57, but the probe centre of gravity 96 can also be offset from the axis of CMM Joint7 57 such that this first embodiment is fully operable up to a maximum permissible torque caused by an offset probe oriented at its worst position relative to the gravitational force.

In a further embodiment, an actuated kinematic mount such as the Autojoint from Renishaw is provided for automatic probe change. In a further embodiment, a side mounting means is provided for attaching a further probe offset to the side of the axis of the probe end. It will be appreciated to someone skilled in the field that any design of probe mounting means and any combination of probe mounting means in any feasible locations can be provided in alternative embodiments.

Multiple probe use

In a measurement application it is often useful to have two probes 90 mounted on the Robot CMM Arm 1 for dual use either for use simultaneously or for use one at a time. This invention is not limited to one or two probes mounted on the Robot CMM Arm but can include a plurality of probes.

An example of dual probe use is when both a contact probe 95 and an Optical probe 91are mounted on the Robot CMM Arm 1 for 3D scanning a tool of an automotive part in the car body coordinate system. The contact probe 95 is useful for referencing the object to be measured using reference artefacts such as tooling balls or cones in known positions/orientations relative to the car body coordinate system. The Optical probe 91 collects data on the surface of the object 9.

In this first embodiment of the Robot CMM Arm invention, provision is made for multiple probe use of the Robot CMM Arm in which a plurality of probes are attached to the probe end of the Robot CMM Arm and can be used alternately to perform their functions without needing to attach or detach a probe. This means that time is saved in the automated measuring cycle and neither the expense and probable inconvenience of a probe changing system, nor the need for manual intervention is required. In a further embodiment, a plurality of mounted probes 90 can be used simultaneously to perform their functions. In a further embodiment, a combination of at least two of a plurality of mounted probes can be used simultaneously to perform their functions.

Probe types

There are many contact measuring probe types for dimensional measurement that can be mounted to the Robot CMM Arm including but not limited to:

- solid touch contact probes 95;
- touch trigger contact probes with at least one switch that emit an electrical signal on contact with an object such as the Renishaw TP6 and the Renishaw TP20;
- force contact probes with at least one strain gauge such as the Renishaw TP200;
- electrical contact probe in which a circuit is made on contact of the probe with an object that is conductive, the object and the Robot CMM Arm being connected by a cable;

such solid, touch, electrical contact and force contact measuring probes having tips of varied shapes such as spherical, point, flat or custom shapes. An example of a custom shape is a contact measuring probe with a V shaped groove used for measuring bent tube. A further example of a custom shape is a contact measuring probe with two orthogonal curved surfaces for measuring the edge of sheet metal.

- wall thickness measuring probes such as ultrasound;
- contact measuring probes to measure other dimensional quantities such as coating thickness

There are many non-contact measuring probe types for dimensional measurement that can be mounted to the Robot CMM Arm including but not limited to:

- point trigger probes
- point distance measurement probes
- stripe probes of all types
- area probes of all types
- wall thickness probes such as ultrasound that send signals through an air, gas or liquid layer situated between the probe end of the Robot CMM Arm and the surface of the pipe

Non-contact optical probes can use monochromatic light or white light. In the case of monochromatic light from a laser, the power of the laser is preferably low such that it is eye-safe and an operator does not have to wear laser safety goggles or the robot's work-area require safety guarding.

There are many contact and non-contact measuring probe types for non-dimensional quantity measurement that can be mounted to the Robot CMM Arm including but not limited to:

- temperature;
- surface roughness;
- colour;
- vibration;
- hardness;
- pressure;
- density;
- flaw, inclusion detection in welds, bonds.

Tools

Although this invention is primarily for measurement, it is inherently a multi-functional design. There are many tools 98 that do not measure that can be mounted on the Robot CMM Arm 1 including but not limited to:

- marking out with a pen, painting
- cutting, grinding, drilling, hammering, bonding, welding
- placement of stickers

The tools 98 can be static or can be power tools with a translation or rotation element and for which power is provided along the arm.

Probe mass

Contact probes typically weigh 50-200g. Optical probes typically weigh 100-2000g. A combination of probes could weigh in excess of 3kg.

Probe architecture and identity

Probes 90 vary considerably in complexity and power. Architecture for an Optical probe 91 that is provided to mount on this Robot CMM Arm 1 invention is disclosed. Referring now to **Figure 27A**, an Optical probe 91 has a probe connector 260 for a probe cable 259 or a bracket cable 257. A probe PCB 270 is provided with probe static memory 261, a probe processor 266, a probe bus controller 267, a probe wireless unit 268 and a probe sensing device 269. Resident in the probe static memory 261 is a Probe Program 272 and a probe identity 271 comprising: a Probe identity number 262, Probe Calibration data 263, Probe Alignment data 264 and Probe information 265. Probe calibration data 263 is data related to calibration of a probe 91 for measurement irrespective of what the probe 91 is mounted on. Probe Alignment data 264 is data related to the alignment of the probe 91 with the Robot CMM Arm 1. Probe information 265 can include but is not limited to: probe type, probe weight, probe centre of gravity position and inertias relative to the mounting reference point, last calibration date, manufacturing date, manufacturer, accuracy and serial number. This first embodiment provides for any probe 90 to have a probe identity 271 stored inside it. The probe identity 271 can be read after the probe 90 has been mounted onto the Robot CMM Arm 1. It can be read along a wired connection or by means of a wireless connection. This means that, each time the probe 90 is calibrated, the probe calibration data 263 stays with the probe 90 and the chances of it being lost or incorrectly replaced with older probe calibration data 263 in an organisation's IT system are reduced. The probe program 272 can be automatically updated from the laptop 151 or even remotely over the internet or intranet via the laptop 151 or the probe wireless unit 268. This first embodiment further provides that simple probes 90 that do not have a digital identity stored in them can also be used. The probe digital identity is not limited to being stored in probe static memory 261, it can be stored in any form of digital memory with a life in excess of the probe 90 design life without electrical power. There is processing of raw data from the probe sensor 269 by the probe processor 266 and further processing by the laptop 151. In some probe architectures, most or all of the processing is done by the probe processor 266. In other probe architectures, most or all of the processing is done by the laptop 151.

Probe connections and probe cables

Most probes available on the market and particularly Optical probes 91 have proprietary connections, but custom Optical probes 91 are often developed to interface onto localisers. The first Probe Mounting Means 244 provides a Renishaw M8x1.5mm threaded hole with automatic electrical contact for a wide range of Renishaw probes. The second probe mounting means 247 provides a standard thread, but no electrical contact. The third probe mounting means 251 provides a proprietary mechanical mounting and automatic electrical connection arrangement through recessed probe connector 255, which can only be used with permission of the owners of the intellectual property for the design of the third probe mounting means 251. Manual connection of a probe can be made by plugging a short probe cable 259

into additional recessed probe connector 258 situated on CMM Segment8 38. In a not preferred embodiment, a probe cable 259 can be run down the exterior of the Robot CMM Arm 1 and connected into the interface port 194 at the base 4 of the Robot CMM Arm 1.. Those skilled in the field will know that cabling is invariably a problem with articulated arm robots and that running a cable from the probe end of the Robot CMM Arm where no provision has been made for proper routeing around the joint is undesirable. The connector and connections of interface port 194 are preferably the same as for recessed probe connector 255 and additional recessed probe connector 258. Probe electrical connection means 243, 255, 258 and 194 provide one or more of the following: power, ground, trigger and data. Referring now to **Figure 27B**, in a further embodiment, three probe connectors 260 are provided on the probe 90; three probe cables 259 connect the probe 90 to: the Robot CMM Arm 1 via probe electrical connection means 258; the laptop 151 and a probe control box 295. The probe control box 295 is required where it is necessary to minimise the size and weight of the probe 90 and it is practical to remove items from the probe 90 to a separate probe control box 295. Referring now to **Figure 27C**, in a further embodiment, a probe cable 259 connects to the probe connector 260 on the probe 90 and is run along the outside of the Robot CMM Arm 1 to the probe control box 295. A probe box to laptop cable 297 connects the probe control box 295 to the laptop 151. A probe box to arm cable 296 connects the probe control box 295 to the interface connector 194 on the Robot CMM Arm 1. Referring now to **Figure 27D**, a preferred embodiment for interfacing a probe control box 295 to the Robot CMM Arm 1. A probe cable 259 connects to the probe connector 260 on the probe 90 and to the recessed probe connector 258 on the Robot CMM Arm 1. A probe box to arm cable 296 connects the probe control box 295 to the interface connector 194 on the Robot CMM Arm 1. The scope of this invention is not limited by the probe electrical connections and cables disclosed, but includes all types of probe wired and wireless connections. For instance, a probe 90 can send data directly to the laptop 151 by means of a wireless communication such as IEEE 802.11b (WiFi).

Probe specification and performance

The specification and performance of the probe 90 to a large extent determines how the Robot CMM Arm 1 conveys the probe 90 in a measuring task. As previously disclosed, there are many general types of probe 90 that can be used in this Robot CMM Arm invention and for each general type, there are a wide range of designs. A preferable optical probe 91 mounted on a Robot CMM Arm 1 is a Stripe probe 97. Referring now to **Figure 28**, a Stripe probe 97 contains a laser light source 298 and a plane generating optic 299 that projects laser light 280 fanned out to either side of the direction +Z, approximately represented by a triangular segment of a plane. Measuring takes place within a polygonal segment 281 constructed from a minimum stripe length 284 closer to the Stripe probe 97 and a maximum stripe length 285 further from the Stripe probe 97. The distance between the minimum stripe length 284 and the maximum stripe length 285 is the depth of field 282. The standoff distance 283 is the distance from the Stripe probe 97 to the middle of the polygonal segment 281. A sensing device 269 in

the Stripe probe 97 collects the laser light 280 via a lens 300 in a view 302 at a standoff triangulation angle 286 and with a scanning rate 294 in stripes captured per second. Referring now to **Figure 29**, a Stripe probe 97 mounted on a Robot CMM Arm 1 scans an object 9 by moving relative to it in direction X at surface speed 293 in mm/second. A stripe 287 is formed on the surface of the object 9 by the projected laser light 280. Measurements are made along the stripe 287, providing it lies within the polygonal segment 281. Referring now to **Figure 30**, the stripe 287 on the object 9, is divided into a sequence of N small areas 288 in the Y direction that correspond to individual 3D measurements output by the probe. The average point separation 289 between neighbouring small areas 288 along the stripe 287 is distance DY. Referring now to **Figure 31**, a series of stripes 287 in the direction X on an object 9 are captured. The average stripe separation 290 is distance DX. The series of stripes 287 form a scanned patch 291. Referring now to **Figure 32**, an object 9 is scanned in a series of overlapping scanned patches 291 with a nominal overlap distance 292. Referring now to **Figure 33A**, a two-view stripe probe 301 comprises two sensing devices 269 and lenses 300 with two opposing views 302 and 303. Referring now to **Figure 33B**, the two-view stripe probe 301 views an object 9 with a step 304. First view 302 has a clear path to the stripe 287 where laser stripe 280 illuminates the object 9. Second view 303 has a path to the stripe 287 that is occluded by the step 304 in the object 9 and cannot see image the stripe 287 in this location. Referring now to **Figure 34A**, a two-stripe probe 308 comprises a central sensing device 269 and lens 300 with a view 302, two laser light sources 298 and plane generating optics 299 that projects a first laser light plane 305 and a second laser light plane 306 crossing at line 307. Referring now to **Figure 34B**, the two-stripe probe 308 views an object 9 with a step 304. First laser light plane 305 illuminates the face of the step 304 of the object 9 forming stripe 287 and view 302 has a path to the stripe 287.

The following parameters of the probe affect at least the programmed movement of the Robot CMM Arm 1 and are disclosed in more detail:

- **stripe length**: a stripe probe 97 is usually specified by maximum stripe length 285; in practice, the actual stripe length will vary depending on the distance from the stripe probe 97 to the object 9; for a flat object 9 of height 500 mm, with a maximum stripe length of 75 mm from the probe 97 and an overlap of up to 25mm, the object can be scanned in ten patches with a 50mm increment between each patch; the longer the stripe length, the smaller the number of patches required; stripe lengths typically vary from 10mm to 200mm but can be more or less; stripe lengths overlaps typically vary from 5% to 50% of the stripe length depending mainly on the shape of the object 9 but can be more or less
- **average point separation**: a stripe is actually output as a discrete series of 3D points; a typical number of points in a stripe N is currently of the order of 750, although this is expected to increase in the future; if a stripe length is 75 mm, then the average point separation along the stripe is 0.1mm; objects 9 with detailed features can require scanning with a smaller average

point separation of 0.01-0.05mm or less; large objects 9 with few features can require scanning with an higher average point separation of 0.25-1mm or more

- **scanning rate (stripes/second):** typical current scanning rates 294 are from 25 to 60 stripes per second; scanning rates are expected to increase in the future; there are a variety of possible scanning rates:
    - o constant scanning rate: the time between any two stripes is always the same; this is common for a sensing device 269 that is a video sensor
    - o two alternative constant scanning rates: this is common for a sensing device 269 that is an interlaced video sensor; CCIR rates of 25 or 50 stripes per second are common; NTSC rates of 30 or 60 stripes per second are common; the higher scanning rate produces lower resolution data; the operator can select which scanning rate to use at a time
    - o any constant scanning rate up to a maximum scanning rate: the operator sets the rate he wants
    - o triggered variable rate: the time between stripes can vary; another event can trigger the stripe probe 97
    - o processing variable rate: the time between stripes can vary; the processing time of each stripe can vary; the next stripe is not captured until the previous stripe has been processed
- **surface speed**: there are a variety of possible surface speeds:
    - o constant surface speed: stripe probe 97 moved over object 9 at a constant surface speed 293; the stripe probe 97 can be at a constant orientation or a changing orientation; the stripe probe 97 is moving relative to the object whilst measuring takes place
    - o variable surface speed: the surface speed 293 varies during scanning; there can be many methods for varying surface speed; for instance if a surface is featured in some areas and smooth in other areas, then it is often desirable to scan featured areas more slowly
    - o stepwise: the stripe probe 97 is moved from position to position by the Robot CMM Arm 1; at each position the stripe probe 97 is static whilst measuring takes place; stepwise scanning is used to achieve the highest accuracy measuring; in the case of a moving object 9, the stripe probe 97 is in a constant position relative to the object 9 whilst measuring takes place
- **average stripe separation:** if the Robot CMM Arm is moving in a direction orthogonal to the stripe at a surface speed 293 of 30mm/second, then at a scanning rate of 60 stripes/sec, the average stripe separation 290 will be 0.5mm; objects 9 with detailed features can require scanning with a smaller average stripe separation of 0.05mm or less; in this case, the speed of the Robot CMM Arm must be reduced to 3mm/second; large objects 9 with few features can require scanning with an higher average stripe separation of 1mm or more

- **evenness of stripe separation:** Robot CMM Arms can scan at a constant surface sp[illegible]; operators of Manual CMM Arms cannot scan at a precise and constant surface speed; this means that a Robot CMM Arm can provide a more even stripe separation than a Manual CMM Arm;
- **uniform 3D point density:** this is desirable in some applications; Robot CMM Arms can achieve uniform 3D point density by setting a surface speed such that the average stripe separation is equal to the average point separation; uniform 3D point density can also be achieved by sampling points along the stripe to increase the average point separation
- **depth of field:** 3D points can be measured over a depth of field 282 that is typically between 50 and 200 mm deep; in general, the larger the depth of field, the worse the Root Mean Square (RMS) Z noise of the 3D points from the stripe probe 97; current stripe probes have a RMS of around 1/10,000 of the depth of field; for example a stripe probe 97 with 70 mm maximum stripe length and 100 mm depth of field has an RMS of 10 microns in the Z direction
- **standoff**: the standoff 283 is typically between 75 and 300 mm; ideally, the standoff should be large to (a) reduce the risk of collisions between the Robot CMM Arm 1 and the object 9 and (b) maximise penetration into deep regions such as slots; as the standoff increases, so does the virtual reach 81 of the Robot CMM Arm; as the virtual reach 81 of the Robot CMM Arm increases, the accuracy of the Robot CMM Arm and the accuracy of the probe 91 both decrease; the selection of standoff is thus a compromise between accuracy and application
- **occlusion**: a two-view stripe probe 301 mounted on a Robot CMM Arm 1 has the advantage over a stripe probe 97 with one view of capturing more data from stripes 287 on an object 9 that has steps or similar features causing occlusions; there are more cases for the stripe probe 97 than for the two-view stripe probe 301 in which an area has to be re-scanned in a different orientation to reach surface areas of the object 9 that were occluded in the first patch captured; this means that the total measurement time is reduced for the two-view stripe probe; however, the two-view stripe probe 301 is more bulky and heavier than the stripe probe 97. A preferred two-stripe laser probe 308 mounted on a Robot CMM Arm 1 has the advantage over a stripe probe 97 or a two-view probe 301 in that it can capture data on a vertical step wall 304.
- **automation**: the Robot CMM Arm is automated and can scan continuously for more than 24 hours; by comparison, the operator of a Manual CMM Arm gets tired; this means that the Robot CMM Arm can scan more and better quality data from an object 9 than a Manual CMM Arm used by an operator

The laser source 298 is a laser diode of 30 mW power of approximately 660nm wavelength as can be purchased from a variety of suppliers including Toshiba Japan. The optics 300 is a Light Pen from Rodenstock, Germany. The sensor 269 is a CCD NTSC video sensor chip as can be purchased from a variety of suppliers including Sony either as a chip or a board camera. The scope of this invention is not limited in any way to this design of optical probe but can incorporate any suitable design of optical probe. Projected light sources can include light of any type such as: white light; laser radiation that is

invisible, infra-red, ultraviolet, partially visible or fully visible. Multiple projected light sources can be employed of different specific wavelengths or different wavelength bands that can be later differentiated by bandpass filters and multiple sensors 269. Projection optics 299 and imaging optics 300 can be static or dynamic. Dynamic optics include amongst others galvanometer mirrors and rotating polygonal multi-mirrors. The projected light sources can be at constant power or the power can vary. Light projection can be always on or strobed. Sensing devices 269 include amongst others devices made of CCD and CMOS technologies. Sensing devices 269 can be analogue devices such as 1D and 2D PSD devices. Sensing devices 269 can be digital devices with pixels such as a 1D line of pixels or a 2D array of pixels. Sensing devices 269 can have different fill factors and can employ microlenses. Sensing devices 269 can have fixed or variable shutter speeds. Strobing of light projection can have the light on over all or part of the shutter open time.

Power supply

The electric power consumption of a Robot CMM Arm disclosed in this first embodiment is typically less than 1 kW and in most cases less than 2 kW. This means that home/office mains supply of 80-240V can be used and there is no need for 3-phase supplies running at higher voltages. A standard IEC socket 195 is provided for mains power connection via cable 155. For site applications such as scanning corroded gas pipes, provision is made for Robot CMM Arm operation from 24V DC that is supplied by a 24V battery of the type used in vehicles. A 24V DC socket 195 and a 24V cable 155 that is 20m long are provided. A Sony rechargeable battery 170 is provided as a backup power supply enabling backup activities such as saving encoder positions to take place in the event of a sudden power cut, such that operation of the Robot CMM Arm can resume immediately that full mains power is restored without having to carry out initialisation procedures. The battery 170 is removable.

Robot CMM Arm Cables and PCB positions

Internal cables 165, 166, 167, 169, 174 and 196 run along the Robot CMM Arm 1 from the control box 159 to the probe end 3 connecting the Joint PCBs 173 and motors 176. The Internal cables 165, 166, 167, 169, 174 and 196 run between the Internal CMM Arm 5 and the Robot Exoskeleton 6. This means that all the cables are protected within the exterior surface of the Robot CMM Arm 1. The Joint PCBs 173 are situated between the Internal CMM Arm 5 and the Robot Exoskeleton 6. Most of the devices 177-184 local to the Joint PCBs 173 are mounted on either the Internal CMM Arm 5 or the Robot Exoskeleton 6. Each Joint PCB 173 is connected to at least one of the local devices 177-184 by wires, ribbon cables or circular-section cables that run between the Internal CMM Arm 5 and the Robot Exoskeleton 6. The Internal cables 165, 166, 167, 174 and 196 as well as the wires connecting devices 177-184 to the Joint PCBs are of standard and robust formats, commonly used in the art. The gauge of the cables is kept to a minimum to reduce weight. The serial cable 169 is a IEEE-1394 Firewire cable. Probe box-arm cable 296 is a customised cable provided for the specific requirements of the probe box

or other interface device related to the services supplied by the Robot CMM Arm 1 through inte. .e connector 194. Laptop cable 152 is a Firewire IEEE-1394 cable from a Firewire connector 197. Network connector 199 is a 100 Mbps Ethernet connector and connects to Ethernet network 200 of standard CAT5 cabling. Pendant cable 154 is a Firewire IEEE-1394 cable from a Firewire connector 198.

The scope of this invention is neither limited to the internal cabling disclosed, nor to the PCB arrangements disclosed. Optical probes are increasing in bandwidth of output data to be transferred to the processing unit. High bandwidth serial cables are available such as those specified in IEEE-1394b Firewire.B that has bandwidth of up to 3.2 GB/sec using optical signal cables but less bandwidth with electrical signal cables. Optical signal cables are largely immune to electrical noise and can carry signal for long distances without degradation. This makes them suitable for robot use in which both extended distances and cables routed close to noisy electric motors are a feature. As will be well understood by a person skilled in the art, the number and functionality of PCBs in the Robot CMM Arm can vary without affecting the technical effect of the present invention. For instance, instead of seven Joint PCBs 173, three Joint PCBs 173 can be provided that are located at the shoulder elbow and wrist of the Robot CMM Arm.

<u>User Interface</u>

Laptop PC

Referring now to **Figure 35**, a laptop PC 151 is preferably provided for the main user interface. An adjustable platform 310 is provided for the laptop PC 151 mounted off the base 4 of the Robot CMM Arm 1. A battery 164 in the laptop is provided for operation without mains power connection. Room on the platform is provided for a mouse 311. This invention is not limited to a laptop user interface. A full PC cabinet could be provided; a separate LCD screen could be connected to it. A tablet PC could be provided. The display could have a touch sensing capability. Where two or more Robot CMM Arms are working in a cell, a single laptop PC is preferably used to control all the Robot CMM Arms in the cell. A compact printer 312 is preferably provided connected to the laptop 151. It is used at least to print out measurement records. A place for the printer is provided on the platform 310 under the laptop 151.

Pendant

Referring now to **Figure 36**, a hand-held pendant 153 is provided for local control of the Robot CMM Arm 1; it is provided with both wired 164 and wireless 324 connection to the Robot CMM Arm 1. A battery 163 in the pendant 153 is provided for operation without mains power connection. A recharging point 158 is provided on the Robot CMM Arm 1 where the pendant 153 can be left, typically overnight, for recharging; a feature of the recharging point 158 is that the connection is automatically made, the

pendant is simply placed in the cradle at the correct position and orientation such that the pendant electrical contacts 327 make contact with the recharging point electrical contacts 328. The pendant 153 preferably has an 8" LCD display 322 but it could be smaller or larger; alternatively no display can be provided on the pendant. The pendant is provided with a microprocessor 323, Microsoft Windows CE operating system 326 in memory 325, pendant software 330 in memory 325 and 3D graphics chip 329. The pendant display 322 shows all the results from the use of the Robot CMM Arm 1 including real-time rendered 3D colour graphical displays of scanned data. Such real-time rendering provides help with teach programming. The pendant has a number of buttons 320 for controlling the two directions of movement of each axis. The buttons are fabricated in a membrane technology. A 3-axis joystick 321 is provided, although it can be more or less axes and there can be two or more joysticks or trackballs. In an alternative embodiment, the pendant 153 is not provided or is an option; software on the laptop is provided to carry out the user interface functionality of the pendant. Green LEDs 157 are provided on the Robot CMM Arm 1 and the pendant 153 to show that the power is switched on. All further operational information is shown on the display screens of the laptop 151 or pendant 153.

Head mounted control

Referring now to **Figure 37**, a headset 340 is provided for the operator 11 with wired or wireless contact to the laptop 151. The headset 340 comprises a monocular display 341 of resolution of at least 800x600 pixels situated so that the operator 11 can view it with one eye. The operator 11 can still view the environment around with both eyes, although the eye that can view the monocular display 341 is somewhat obstructed. Monocular displays 341 with higher resolutions are becoming available and can be built into the headset 340. The headset 340 also comprises headphones 343 and microphone 342. The operator 11 uses a small dictionary of commands to control the Robot CMM Arm 1 by speaking into the microphone 342. Each operator 11 preferably teaches the Robot CMM Arm 1 the commands such that the voice recognition software on the laptop 151 will provide a higher rate of recognition. Voice synthesis software on the laptop 151 will voice speech to the operator 11 via headphones 343 to provide a closed loop voice-driven user interface.

Buttons

Referring now to **Figure 38A**, several sets of buttons 183 are fixed onto the Robot CMM Arm that operate in parallel. It is preferable that the set is a pair of buttons 183 for control. A pair of buttons 183 is situated at the probe end 3 of the Robot CMM Arm on Segment 8. The buttons are referred to as A and B, with A closest to the probe end 3. A is coloured Red and B is coloured Green. The buttons 183 are approximately 25mm apart between centres and 11mm diameter. The buttons 183 are recessed to reduce occurrences of accidental actuation. The buttons 183 are large diameter to suit the thumb or finger print size. The buttons 183 are used for control of the measuring of the Robot CMM Arm 1 and selection of software choices. Other pairs of buttons 183 that operate in parallel to the probe end pair

are situated: at the probe end 3 on RobotSegment8 48 at the other side of RobotSegment8 48 from the first pair; on the control box 159 and between the elbow and the wrist on Robot Segment5 45. Referring now to **Figure 38B**, wireless footswitches 350 are provided. Referring now to **Figure 38C**, a wireless remote control 351 with buttons is provided; it is affixed to the Robot CMM Arm at the choice location of the operator 11 preferably with a strap 352; alternatively, the operator 11 can hold the remote control 351. This invention is not limited to the disclosed number of buttons 183 and their situation. The Robot CMM Arm could be operated without any buttons attached to it, using other means such as the pendant 153 or the laptop 151. Control can be achieved with a single button 183 or with 3 or more buttons in each set. A single set or multiple sets can be provided. Factors affecting the number of sets and their location include the reach of the Robot CMM Arm 1 and the application for which it is used.

Environmental Operation

The portable Robot CMM Arm 1 of this first embodiment is able to operate in temperature ranges of –10 to +50 degrees Celsius. Measuring applications such as Alaskan gas pipelines and Egyptian Tombs are envisaged where the Robot CMM Arm 1 is operating outside in conditions varying from frozen to direct sunlight. The Robot CMM Arm is weather resistant, with environmental sealing level IP62. Alternative embodiments of the Robot CMM Arm can be protected to IP64 level or even have special protection for specialist applications where the environment is harsh such as in radioactive areas. The portable Robot CMM Arm 1 can also operate in up to 90% humidity.

Robot CMM Arm Coordinate Systems

Referring now to **Figure 39**, there is a multitude of Coordinate Systems 360 for the Robot CMM Arm system 150. These include but are not limited to:

- Object coordinate system 361
- Object feature coordinate system 362
- Robot CMM Arm coordinate system 363
- Probe (or Tool) coordinate system 364
- Robot Exoskeleton coordinate system 366

The Object coordinate system 361 can not be known unless there are datum features such as tooling balls 368 on the object 9 or any reference plate that the object 9 is mounted on that can be used to provide an Object coordinate system 361 for the object 9. The most common provision in the automotive industry is that of the car line object coordinate system 361. An object feature coordinate system 362 is provided for a feature 365. Often objects are manufactured with reference marks for an object feature coordinate system 365 that can be measured to determine the object feature coordinate system 365. In this first embodiment, the Robot CMM Arm coordinate system 363 that is also known as the Internal CMM Arm coordinate system and the Robot Exoskeleton coordinate system 366 are identical because the Internal CMM Arm base 31 and the Robot Exoskeleton base 41 are rigidly

,onnected. A reference ball 367 that is 25mm in diameter is provided in a repeatable magnetic mount 369 at the base 4. The centre of the reference ball 367 is nominated as the zero of the Robot CMM Arm coordinate system 363 and the Robot Exoskeleton coordinate system 366. When the Robot Exoskeleton has a different base 41 from the Internal CMM Arm base 31, particularly if there is relative movement between the Robot Exoskeleton base 41 and the Internal CMM Arm base 31, then the Robot Exoskeleton coordinate system 366 is different from the Robot CMM Arm coordinate system 363; in this case, a second reference ball 367 is provided. As is commonly understood in the field of robotics, there is provided a different coordinate system for a probe 90 or tool 98 affixed to the probe end 3 of the Robot CMM Arm 1. It is referred to as the Robot CMM Arm probe coordinate system 364.

Control PCB

Referring now to **Figure 40**, the Control PCB 172 controls the Robot CMM Arm 1. The external connectors, 156, 157, 194, 195, 197-199 are mounted on the Control PCB 172 and attach directly to the side of the control box 159. Interfacing to the arm is by means of amplifier analogue output circuitry 383, trigger circuitry 384, Firewire bus controller 385, Ethernet bus controller 386 and WiFi wireless unit 387. A DSP processor 380 runs control software 382 in memory 381. The control software can access kinematics software 391 in memory 381. Programs 389 in a text format are interpreted by an interpreter 390. The Robot CMM Arm Internet Protocol (IP) address 388 is stored in memory 381. The probe alignment file 264 is stored in memory 381. The memory 381 is composed of sufficient static and dynamic memory.

Joint PCB

Referring now to **Figure 41** and again to Figure 11, the Joint PCB 173 has the functions of:

- interconnecting a number of local devices 177-184, 90, buses 169, 174, 161, 162 and power lines 165, 166, 160 all via connectors 400
- responding to trigger signals on the trigger bus 174 by latching an encoder 178
- receiving data from a number of sensors 178-184, pre-processing the data, keeping the status of the data such as encoder counts and sending pre-processed data by serial bus 169 to the Control PCB 172
- responding to status requests from the Control PCB 172

The Joint PCB 173 comprises a DSP processor 401, Memory 402, Joint software 405 resident in memory 402, trigger circuitry 384, Firewire bus controller 385 and encoder interfacing circuitry 403 that connects to the output of the Renishaw Interpolator 187. The count 404 of the interpolated signals from the Renishaw Interpolator is stored in the memory 402.

Thermal compensation

It is an object of this invention to provide a Robot CMM Arm that is thermally compensated and does not require recalibration when the temperature of the Robot CMM Arm changes. Thermocouples 180 are bonded to the Aluminium of each of the housings, 100, 101, 103 of the Internal CMM Arm 5. The CMM Segments1-8 31-38 are designed using finite element software to expand/contract linearly with temperature and not to twist. Similarly, the CMM Segments1-8 31-38 are manufactured using well known processes and materials that do not result in stresses that might cause distortion with changes in temperature. Aluminium expands at a well-known rate with temperature. The thermocouples 180 are read every 10 seconds by the Joint PCBs 173 and the temperatures are sent to the Control PCB 172 along the serial bus.169. Some of the parameters in the 45-parameter.kinematic model of the Internal CMM Arm are then adjusted in proportion to changes in temperature measured by the thermocouples 180 in each housing in ways predicted by the finite element thermal modelling. Where extremes in temperature are encountered such as in Alaska or the desert, it is recommended that a contact or non-contact probe alignment takes place before the Robot CMM Arm is used.

Monitoring Forces and Torques

During measuring the Internal CMM Arm 5 is subject to forces and torques. Strain gauges 181 mounted on CMMSegments1-8 31-38 sense the strains on the Internal CMM Arm 5 continuously. Three strain gauges 181 are mounted orthogonally on each CMM Segment 1-8 31-38. The strain gauges 181 are connected to the Joint PCBs 17. The Joint PCBs 173 send values read from each strain gauge 181 to the Control PCB five times per second. Strain values could be sent more often or less often than 5 times per second. During setup, after the manufacture of each Robot CMM Arm, a series of strain gauge test programs are run and the values output from each strain gauge are monitored during the execution of the program. Some of the test programs are designed to over-strain the Internal CMM Arm 5; one method used is to move the arm rapidly with a heavy dummy probe 90 mounted on CMM Segment8 38. In this way, the strain gauges 181 are calibrated with maximum acceptable compressive and tensile strains. In normal use, the strains from all the strain gauges 181 are monitored 5 times a second and if a maximum acceptable strain is exceeded, then action is taken. Actions include: generating an error message to the operator, automatically repeating some measurements at a slower speed to reduce the strain levels, logging the unacceptable strains and the conditions under which they are produced.

Timing

Measuring can take place on the fly or when the Robot CMM Arm is stationary. Precise timing between the Control PCB 172 in the Robot CMM Arm 1 and the Optical Probe 91 is crucial for maintaining high accuracy when measuring takes place on the fly. Two methods of ensuring precise timing between the Control PCB 172 and the Optical Probe 91 are preferably Synchronisation and also Time-stamping. The

scope of this invention is not limited by these two methods and includes any method of ensuring precise timing between the Control PCB 172 in the Robot CMM Arm 1 and the Optical Probe 91.

Synchronisation

The Synchronisation method is characterised by pairs of synchronised measurements, the first measurement being the probe measurements and the second measurement being the position of the Internal CMM Arm 5. Referring now to the process of **Figure 42**, when data from the Control PCB 172 and the Optical Probe 91 is synchronised then in a first synchronisation mode, the Optical Probe 91 is preferably the master and the Control PCB 172 is the slave. In a first step, Step 410, the Optical Probe 91 sends a synchronisation signal over the Trigger bus 174 to the seven Joint PCBs 173. The synchronisation signal travels fast over the Trigger bus 174 with a delay of less than 1 microsecond. In Step 411, probe measurements and position data are sent to the laptop 151. The Joint PCBs 173 send encoder data to the Control PCB 172. The Control PCB 172 assembles the seven encoder positions, calculates the position of the Internal CMM Arm 5 at the probe end 3 and sends the position to the Laptop 151. The Probe 91 sends probe measurements to the Laptop 151. In Step 412, the Laptop 151 combines the probe measurements and the position of the Internal CMM Arm 5 to provide measurements. This method works when the synchronisation signal has a delay longer than 1 microsecond to travel from the Optical Probe 91 to the Control PCB 172 providing the synchronisation method and apparatus has the technical effect of capturing probe measurements and encoder positions such that they can be combined to produce accurate measurements. Referring now to **Figures 43A-C**, the Optical Probe 91 is the master and the Control PCB 172 is the slave. Referring now to Figure 43A, to measure, an active Optical Probe 91must satisfy two conditions: light must be projected and the sensor shutter must be open to collect light. In the mode of Figure 43A, measuring takes place when the laser is on. A synchronisation signal should be sent from the optical probe 91 to the Control PCB 172 at time T, which is the midpoint of the measuring period P. In this first embodiment, the Robot CMM Arm 1, on receipt of a synchronisation signal at time T, can latch the encoders in a repeatable time that is less than 1 microsecond. Referring now to Figure 43B, the measuring period P is from the opening of the shutter to the laser switching off. Referring now to Figure 43C, the measuring period P is when the shutter is open.

Synchronisation can take place in a second synchronisation mode when the Control PCB 172 is the master and the Optical Probe 91 is the slave. An example of such synchronisation is when the scanning mode is to measure at regular arm increments and the Control PCB 172 is master. Referring now to **Figure 44**, a synchronisation signal arrives at Optical probe 91 at time T from the Control PCB 172. It is preferable that both the laser turns on and the shutter opens within a short period of time after T. In the case of Figure 44, the shutter determines the measuring period P and has a centre that is delayed by t microseconds after time T. In other cases the laser determines the measuring period P or a combination

of the shutter and the laser determines the measuring period P. It is important that, in order to maximise the accuracy of the Robot CMM Arm 1 when scanning on the fly, delay t is known and repeatable for all measurements in this second synchronisation mode. In some Optical Probes 91, delay t is changed between measurements by the Optical Probe 91. In this case, the Optical Probe 91 communicates changes in the value of delay t over the serial bus 169 before the next synchronisation signal is received. Referring now to the process of **Figure 45**, in a first step 413, the Optical Probe 91 sends a change in the value of delay t to the Control PCB 172. This step 413 is only executed if delay t has changed. In step 414, the Control PCB 172 sends a probe synchronisation signal to the Optical probe 91 at time T. In step 415, the Control PCB 172 sends an encoder synchronisation signal to the seven Joint PCBs 173 at time T+t. The Control PCB uses a means such as an internal clock to determine the correct moment to send the encoder synchronisation signal after the probe synchronisation signal. It is an object of this invention that in a first synchronisation mode of use, the Control PCB 172 is the master and the Probe 90 is the slave and in a second synchronisation mode of use, the Probe 90 is the master and the Control PCB 172 is the slave.

Time-stamping and Interpolation

In some cases, it can not be possible to precisely synchronise the Optical Probe 91 and the Control PCB 172 to produce a pair of measurements. For instance, synchronisation is not possible if means for sending or receiving a synchronisation signal are not provided. In the time-stamping scenario there are two cases: (i) the Optical Probe 91 and the Control PCB 172 have the same measurement rate (ii) the Optical Probe 91 and the Control PCB 172 have different and or variable measurement rates.

In Case (i) the measurements are made in pairs. It is important that the rates of measurement of the Optical Probe 91 and the Control PCB 172 are precise and do not drift over time. Two clocks in the Optical Probe 91 and the Control PCB 172 run accurately such that they show the same times at the start and at the end of the scanning. Measurements in the Optical Probe 91 and the Control PCB 172 take place at the same rate such that there is always the same time interval I between two neighbouring optical measurements and two neighbouring position measurements. Typical rates vary from 25 measurements per second to 1000 measurements per second but could be more than 1000 or less than 25. In Case (ii) the measurements stream out of the Optical Probe 91 at regular or irregular intervals and out of the Control PCB 172 at the same or different regular or irregular intervals.

Referring now to the process of **Figure 46**, the same process is used for both Cases (i) and (ii).

- In first Step 416, the two clocks in the Optical Probe 91 and the Control PCB 172 are synchronised as closely as possible just before the scanning starts;
- In Step 417, measuring is started by the Control PCB 172 requesting the Optical Probe 91 to start scanning;

- In Step 418, position data is captured by the Control PCB 172; each position is time-stamped with the clock in the Control PCB 172. Measurements are captured in the Optical Probe 91; each position is time-stamped with the clock in the Optical Probe 91;
- In Step 419, The Robot CMM Arm scanning program stops and requests the Optical probe 91 to stop scanning;
- In Step 420, the two clocks in the Optical Probe 91 and the Control PCB 172 are checked against each other;
- In Step 421, the Control PCB 172 outputs a file of time-stamped positions. The Optical Probe 91outputs a file of time-stamped measurements;
- In Step 422, a combined measurement file is calculated by interpolating the Control PCB 172 positions to provide a best estimate of where the Internal CMM Arm 5 is for each Optical Probe measurement. Each Internal CMM Arm 5 position contains X, Y, Z position of the probe end 3 and I, J, K orientation vectors. Interpolation of the Internal CMM Arm 5 positions is by fitting a 3D polyline through the Internal CMM Arm 5 positions and interpolating along the 3D polyline in proportion to the time-stamp timing differences.

The scope of this invention is not limited to the process in Figure 46 of time-stamping and interpolation but includes any process involving time-stamping and interpolation that achieves the same technical effect. For instance, where it is not possible to precisely synchronise the two clocks in the Optical Probe 91 and the Control PCB 172, then a method involving first scanning a known artefact is used. Referring now to **Figure 47**, a ridge artefact 370 with two planes meeting at 90 degrees is positioned with the ridge approximately parallel to the laser stripe 287. Two scanning passes are made over the ridge artefact 370 by the Optical probe 91 mounted on the Robot CMM Arm 1. The first pass 371 is in the +X direction and the second pass 372 is in the –X direction. The probe measurements and the arm positions in the two time-stamped files are combined using an estimate of the synchronisation between the two clocks. Referring now to **Figure 48**, when the two passes 371, 372 are compared then an error E as a distance in the X direction is calculated. The error E is used to accurately determine the difference in synchronisation of the two clocks. That difference is then used as a correction factor to the estimate of the synchronisation between the two clocks to provide an accurate synchronisation between the two clocks when an object 9 is subsequently measured.

Measurement Programming

Quick and easy programming of a Robot CMM Arm 1 is important because in general robots require skilled operators to program them and this is one of the challenges that will make a Robot CMM Arm 1 successful in the marketplace. Robot CMM Arm Programs 389 are interpreted in real-time by an Interpreter 390 and commands in a program 389 are executed by the Control Software 382. A program 389 can be generated in a number of different ways.. A text editor is provided for the operator 11 to

generate and edit a Robot CMM Arm program 389 on the laptop 151. A program 389 can be gen_ted in an off-line programming system such as EMWorkplace from Tecnomatix. A program 389 can be taught by operator 11 remote activation of the Robot CMM Arm 1 using a pendant 153 or a laptop 151; this means that where access if difficult, teaching can be done remotely without needing to provide gantries for operator access to manually move the Robot CMM Arm.

Start-up checks

The Robot CMM Arm 1 is powered up by connecting to mains cable 155 and switching on using switch 156. The Control Software 382 in the Control PCB 172 self-starts on power up. The first task of the Control Software 382 is to perform a series of start-up checks. It verifies that all aspects of the hardware and software within the Robot CMM Arm that can be checked are operating correctly. The Joint Software 405 in the Joint PCB 173 self-starts on power up. The first task of the Joint Software 382 is to perform a series of start-up checks. It verifies that all aspects of the hardware and software connected to the Joint PCB 173 that can be checked are operating correctly. The Pendant Software 330 in the Pendant 153 self-starts on power up under control of the Pendant operating system 326. The first task of the Pendant Software 330 is to perform a series of start-up checks. It verifies that all aspects of the hardware and software in the Pendant 153 that can be checked are operating correctly. After checking the directly connected hardware of the Control PCB 172, the Control Software 382 checks the seven remote Joint PCBs 173 by requesting a status report over the serial bus 169 from each one. The Control Software 382 then requests a status report over the serial bus 169 from any probe 90 that can be mounted on the Robot CMM Arm 1. When the internal start-up checks are complete, the Control Software 382 attempts to communicate on external buses to equipment including the footswitches 350, the remote control 351, the pendant 153 and the laptop 151. When the full start-up checks are complete, the Control Software 382 in the Control PCB 172 waits for instructions. It will be appreciated by a person skilled in the trade that start-up checks can be performed in many different sequences and can take a short or long time, but that it is undesirable for the Operator 11 to wait more than a few seconds whilst the start-up checking process is underway.

Referencing

It is desirable that the Robot CMM Arm always knows its joint angles. This can be achieved by using absolute encoders and interrogating them via the Joint PCBs 173 on start-up. When incremental encoders are used, it is desirable to maintain power via the battery 170. However, if the Control PCB 172 does not know the joint angles, then a referencing process is needed. The operator 11 initiates the automatic referencing process after first checking that it is safe to do so. During the referencing process, each joint is rotated until a reference position in reached.

Calibration

There are many ways of calibrating a Robot and many ways of calibrating a Manual CMM Arm known to those skilled in the trade and referenced in the background to this invention. Referring now to **Figures 49 and 50**, in this first embodiment, the calibration approach of automatically measuring a known calibration artefact 373 is used. A 45-parameter kinematic calibration model is adopted. The Robot CMM Arm 1 is rigidly attached to surface 7 and measures a calibration artefact 373 also rigidly attached to the surface 7. The calibration artefact 373 comprises a block with four 90 degree cones 375 of maximum diameter 6mm. One of the four cones 375 is located higher than the other three cones 375 which are approximately co-planar. The calibration artefact 373 has been certified and the distances, orientations between the four cones 375 are known precisely. The calibration artefact 373 is stiff and made out of Invar, a material with a low coefficient of thermal expansion. The artefact 373 is rigidly attached to surface 7 by means of bolts 376 through holes 374 that screw into surface 7. In another embodiment, the artefact 373 is rigidly attached to the surface 7 by clamping. A touch trigger probe 92 that is a Renishaw touch trigger probe is mounted on the Robot CMM Arm 1. A calibration program is initiated by the operator 11 and executed by the Control PCB 172. It consists of taking ninety touch-probe measurements of each of the four spheres 375. The joints are exercised as much as possible during the three hundred and sixty touch-probe measurements; this means that measurements are taken with a wide combination of joint angles. None of the 360 touch-probe measurements have identical joint orientations. For each measurement, the seven encoder positions are recorded. Using a least squares process well-known by those skilled in the art, the 360 sets of encoder positions are used to optimize the 45 parameters of the kinematic model. This calibration approach can be used, preferably with a reduced number of measurements to speed it up, to align the probe coordinate system 364 of any contact probe 95 to the Robot CMM Arm coordinate system 363; during this contact probe alignment process, the Robot CMM Arm is preferably not recalibrated, but can also be recalibrated. Referring now to **Figure 51**, in a further embodiment, the artefact 373 is placed in eight locations approximating the eight corners of a cube within the measuring volume of the Robot CMM Arm 1. In each location, 360 measurements are automatically taken. Using the same least squares process, the 8x360 sets of encoder positions are used to optimize the 45 parameters of the kinematic model. These calibration processes simultaneously calibrate the arm and the contact probe. The scope of this invention is not restricted to the automated calibration methods disclosed, but includes any automated, partially-automated or manual calibration method with any contact or non-contact Probe 90 that achieves the technical effect of an accurate calibration of the Robot CMM Arm 1.

Alignment of optical probe

There are many ways of aligning the coordinate system of a Manual CMM Arm and the probe coordinate system 364 of an Optical probe 91 known to those skilled in the trade and referenced in the background to this invention. The preferred way of aligning the coordinate system 363 of the Robot

CMM Arm 1 and the probe coordinate system 364 of an Optical probe 91 is to scan a sphere w_ . the Optical probe 91 mounted on the Robot CMM Arm 1 from a number of different probe directions and orientations. The sphere is preferably 25mm in diameter, certified and with a matt surface finish; such spheres are supplied by Renishaw. In the case of a Stripe probe 97, five Stripe probe directions are used: +X, -X, +Y, -Y, -Z in the Robot CMM Arm Coordinate System 363. For each direction, the sphere is scanned by the Stripe Probe 97 at 45 degree increments in orientation of the stripe plane 280 resulting in 8 orientations from each direction. At each of the 40 direction/orientation combinations, a forward +X scanning pass and a backward –X scanning pass are executed where +X and –X are in the probe coordinate system 364. The resulting 80 sets of Optical probe measurements and arm positions are processed using a least squares algorithm well-known by those skilled in the art, to produce the alignment transformation matrix between the Robot CMM Arm Coordinate System 363 and the probe coordinate system 364. The scope of this invention is not restricted to the automated alignment method disclosed, but includes any automated, partially-automated or manual alignment method that achieves the technical effect of an accurate alignment of the Robot CMM Arm 1 and an Optical probe 91.

Datuming Object

It is often the case that an object 9 is datumed before it is measured. In the datuming process, the transformation matrix between the Robot CMM Arm coordinate system 363 and the object coordinate system 361 is measured. In many instances datum features such as cones, tooling balls and reference planes are provided in accurate locations on the object 9. In the case of datuming an object 9 to the Robot CMM Arm 1, the operator first specifies to the Robot CMM Arm user interface software on the laptop 151 or on the Pendant 154 which datuming method is to be used and the Robot CMM Arm adopts that method. Common datuming methods include: three orthogonal planes; two cones and a plane; three tooling balls. The operator then manually guides the Robot CMM Arm through the sequence of locations necessary to perform the datuming method and the Control PCB 172 applies automated techniques for each measurement once a location is reached.

Feature and surface inspection

The Robot CMM Arm is a measuring machine. Many but not all measurements are carried out for the purpose of inspection. The Robot CMM Arm is particularly appropriate for feature and surface inspection of non-prismatic objects. Typical objects for inspection include those made of sheet metal, plastic or fibreglass and the tools that make these items. The objects are manufactured for example in the automotive, aerospace, appliance and toy industries. The objects are typically made by stamping, cutting, bending and punching processes. Examples of features on the objects that can be inspected include: outside corner, square hole, rectangular hole, oval hole, circular hole, edge profile and inside corner. In many cases a CAD file of the object is available. The CAD file specifies the exact 3D location, orientation, shape of the object's surface and features. Both the object and any tooling used to

make it can be measured and compared to the CAD file. Measurements can be stored for Quality Assurance purposes. Objects can be measured by contact or non-contact probes 90; non-contact probes have the advantage of not touching the object. For the case where a CAD file does not exist or has been lost, a master object or tool can be reverse engineered to provide a master CAD file for subsequent use in inspection.

<u>**Control Software**</u>

The Control Software 382 comprises a variety of manual, semi-automatic and automatic methods of use such as functions and modes. Some of these methods are disclosed below. It will be appreciated by a person skilled in the art, that there are many methods that can be employed for using the Robot CMM Arm provided by the Control Software 382 and that the methods hereby disclosed are exemplary of all methods that can be employed in using the Robot CMM Arm. The following exemplary methods are listed for the Control Software 382:

Continuous scanning: the kinematics module 391 in the control software 382 controls the movement of the Robot Exoskeleton along the path required by the program 389, using control algorithms well known to those skilled in the art of robot controls; this is most often used

Stepwise scanning: the kinematics module 391 in the control software 382 controls the stepwise movement of the Robot Exoskeleton along the path required by the program 389 stopping at points specified in the program 389

Transitioning: transitioning is a movement made during which no measurements are taken; the kinematics module 391 in the control software 382 controls the continuous movement of the Robot Exoskeleton along the transitioning path required by the program 389 without monitoring the strain gauges

Teach: the kinematics module 391 in the control software 382 acts on movement commands specified directly by the operator 11 received via the pendant 153, the headset 340 or the laptop 151

Thermal monitoring: the control software 382 monitors the thermocouples 180 and adapts the kinematic parameters to their temperatures

Strain monitoring: the control software 382 monitors the strain gauges 181 to check for excess strain values in the continuous scanning mode

Collision monitoring: the control software 382 monitors the following error and if it becomes excessive, it applies an emergency stop and issues an error message that could include an audible alert emitted by the loudspeaker in the laptop 151 or through the headset 340

Zeroing coordinate system: the control software 382 zeros a Robot CMM Arm coordinate system 363 by measuring the reference ball 367 with preferably a touch-trigger probe 92 to find its centre and use the centre of the reference ball 367 as the zero point of the Robot CMM Arm coordinate system 363

Datum referencing an object: the control software 382 references the Robot CMM Arm coordinate system 363 to the Object coordinate system 361 through datums. This function is automatic if the

control software 382 knows approximately where to pick up datums on the object 9. This funct.. is semi- automatic if the operator 11 first has to teach the Robot CMM Arm where the datums are on the object 9.

Feature location: the control software 382 measures the location of one or more features on an object 9 relative to the Object coordinate system 361

Dimensional measurement: the control software 382 measures the dimensions of one or more features on an object 9; as will be appreciated by a person skilled in the art, a range of functions are provided for measuring a variety of types of dimension

Surface measurement: the control software 382 measures the surface of all or parts of the Object 9

Software Referencing: the control software 382 references the measured surface data of the Object to the CAD model of the object 9 by a process of least squares fitting

Error generation: the control software 382 compares the measured data of the surface of the Object with a CAD model of the object 9 and generates individual errors and error maps

Report generation: the control software 382 automatically generates a report and/or pass/fail data on the variations of the measured data of the surface of the Object 9 from a CAD model of the object

Statistical trends: the control software 382 compiles statistical trend information as to the location of one or more features on an object 9 relative to the Object coordinate system 361, the dimensions of one or more features on an object and to variations of the measured data of the surface of the Object from a CAD model of the object

Method for Robot CMM Arm Measurement

Referring now to **Figure 52,** in a first step 431, the Control PCB 172 outputs a signal to at least one amplifier 175 that causes at least one motor 176 to output a torque. In Step 432, the drive of the motor causes torque on at least one Robot Segment 42-48. In Step 433, at least one transmission means 72-78 receives force from at least one Robot Segment 42-48. In Step 434, at least one transmission means 72-78 applies force to at least one CMM Segment 32-38 in locations near the centre of gravity of the CMM Segments 32-38. In Step 435, the probe 90 measures data. In Step 436, the Control PCB 172 receives encoder data from the Joint PCBs 173. In Step 437, the Control PCB 172 receives measurement data from the probe 90. In a method for synchronised Robot CMM Arm measurement, in an additional step, the probe 90 sends a synchronisation signal. In a method for time-stamped Robot CMM Arm measurement, the probe measurements and the positions are time-stamped.

Robot CMM Arm Advantages

It is a purpose of this invention that the Robot CMM Arms disclosed here can have longer reach and are more accurate than the equivalent Manual CMM Arms. Firstly, a Robot CMM Arm can have a reach longer than 2 metres because it is supported by a Robot Exoskeleton and not by an operator who could not handle it. Secondly, the Robot Exoskeleton supports the Internal CMM Arm at optimum positions

such that the forces on it are minimised. Thirdly, the Internal CMM Arm uses larger diameter encoders with increased resolution and accuracy that might be awkward for an operator to handle. The combination of these three factors results in Robot CMM Arms that have longer reach and are more accurate than Manual CMM Arms. This means that with the long-running trend of increasing accuracy requirements from customers, a Robot CMM Arm provides more utility to its owner than a Manual CMM Arm.

A feature of this invention is its low weight compared to existing robots. Typical weights vary from 5kg to 35kg, depending on the reach of the arm. This means that smaller and mid-size versions of the Robot CMM Arm invention are light enough to be portable. The portable Robot CMM Arm of this first embodiment comprises a single compact unit; it can be transported by one person in a single case with wheels. A stand can be used which means that the Robot CMM Arm does not need to be bolted to the floor like robots are; this means that the Robot CMM Arm can be quickly moved from location to location.

Applicability

The Robot CMM Arm combines the accuracy benefits of a CMM arm with the flexibility and automation of a robot. This means that it is a preferable means for tackling a host of mid-accuracy measuring tasks for which existing solutions are inferior in one or more of accuracy, flexibility and automation. This Robot CMM Arm invention is both automated and accurate. It fits many requirements of the automotive industry for measurement. It is light and relatively low-cost to manufacture. Automated measurement by the Robot CMM Arm is performed more reliably than manual operation of a Manual CMM Arm, because there is not an operator applying forces and torques that make measurement inaccurate. On a production line, the Robot CMM Arm is lower cost to operate than a manual operator operating a Manual CMM Arm, particularly when working a 2 or 3-shift pattern. It is expected that this invention will be deployed as a general purpose measuring tool for a host of applications similar to the general purpose utility of conventional CNC CMMs.

There are two broad measurement applications: reverse engineering and inspection. This Robot CMM Arm invention is applicable to both, but will see greater deployment in inspection applications because Reverse Engineering is a comparatively rare event compared to regular inspection. The following applications are listed by means of example of the utility of this invention. The application of this invention is not limited to the applications listed below.

Inspection applications

- gap and flush measurement for automotive doors
- verification of dimensional tolerances
- riverbed analysis
- VR simulation

- tooling inspection
- pre-production designs
- development of foams
- car body inspection on production line
- seat inspection on seat production line
- interiors of cars in situ
- engine components removed and in situ
- turbine blades
- housings and cowlings
- gas tank inspection
- glass quality analysis
- interior trims
- prototype assembly of cars; verifying panel has been manually placed in the correct position
- press die
- scanning of bridge support
- sheet metal components: features
- sheet metal components: surface shape
- external pipe corrosion measurement and pipe thickness measurement

Reverse Engineering

- military parts for spares where drawings have been lost
- clay styling models for automotive desi_ _
- industrial design models
- surface reconstruction
- model of character or prop for film/broadcast/computer games animation
- precious artworks such as large sculptures, statues and artefacts for archiving, research, reconstruction and conservation
- rapid prototyping
- detailed objects for which it is too time consuming and arduous to measure manually

Medical

- breast reconstruction
- neurosurgery
- radiotherapy
- robotic surgery

Other

- Haptic Toy for playing with
- research
- teaching

A cell of several Robot CMM Arms is a superior installation to existing rigid structures of static Optical probes on automotive lines. The Robot CMM Arms are more flexible for dynamic reprogramming for different car models going down the line. For optical scanning of a one-off object, a Robot CMM Arm removes hard manual effort from operator and maximises dimensional accuracy by minimising forces on the Internal CMM arm. For applications involving objects that are difficult to access, a gantry is normally built to let the operator measure the object with a Manual CMM arm; often the operator is in an awkward position that can not be safe and can lead to back strain. Applying this Robot CMM Arm invention will mean that the measuring can be manually controlled using a hand-held control panel. This means that a gantry does not need to be built and the operator does not need to get into awkward, unsafe and unhealthy positions for measuring.

_URTHER EMBODIMENTS

This Robot CMM Arm invention is not limited to the portable device of the first embodiment but may include any form of device up to heavy built installations.

CLAIMS

1. An apparatus for determining data of an object, comprising:

- a movable member;
- a movable position reporting device;
- a transmission means by which movement of said movable member causes movement of said movable position reporting device;
- one or more probes disposed on said position reporting device for collecting probe data of said object.

2. Apparatus in accordance with claim 1 wherein said movable member is a robot.

3. Apparatus in accordance with any of claims 1 or 2 wherein said movable position reporting device is a CMM arm.

4. Apparatus in accordance with any of claims 1 to 3 wherein any of said one or more probes is a non-contact probe.

5. Apparatus in accordance with claim 4 wherein said non-contact probe is a stripe probe.

6. Apparatus in accordance with any of claims 1 to 3 wherein any of said one or more probes is a contact probe.

7. Apparatus in accordance with any of claims 1 to 6 wherein said transmission means comprises a plurality of transmission means.

8. Apparatus in accordance with any of claims 1 to 7 that further comprises a data processor that retrieves said probe data from said one or more probes and positions from said position reporting device.

9. Apparatus in accordance with any of claims 1 to 8 in which the probe data and the positions are time synchronised.

10. Apparatus in accordance with any of claims 1 to 8 in which the probe data and said positions are time stamped.

11. Apparatus in accordance with any of claims 1 to 10 in which said movable member and said movable position reporting device have the same joint axis orientations and joint centres.

12. Apparatus in accordance with claim 11 in which said movable member encloses said movable position reporting device.

13. Apparatus in accordance with any of claims 1 to 12 that further comprises one or more strain gauges affixed to said movable position reporting device.

14. Apparatus in accordance with claim 2 in which said robot is anthropomorphic and comprises a series of joints.

15. Apparatus in accordance with claim 14 in which the number of joints in said robot is 6.

16. Apparatus in accordance with claim 14 in which the number of joints in said robot is 7.

17. Apparatus in accordance with any of claims 1 to 16 in which said transmission means are not rigid

18. Apparatus in accordance with any of claims 1 to 16 in which said transmission means are rigid

19. Apparatus in accordance with any of claims 1 to 18 in which one or more tools are disposed on said position reporting device

20. Apparatus in accordance with any of claims 1 to 19 that further comprises a controller for causing said movable member to move in relation to said object.

21. Apparatus in accordance with any of claims 1 to 20 that further comprises a base structure to which the base end of said movable member and the base end of said movable position reporting device are rigidly attached.

22. Apparatus in accordance with any of claims 1 to 20 in which there is relative movement between said base end of said movable member and said base end of said movable position reporting device.

23. Apparatus in accordance with claim 22 wherein said relative movement is measured.

24. Apparatus in accordance with any of claims 1 to 23 that comprises a single unit and is portable.

25. Apparatus in accordance with any of claims 1 to 23 that comprises a separate control box.

26. Apparatus in accordance with claim 7 wherein there is provided a transmission means between each segment on said movable member and each corresponding segment on said position reporting device.

27. Apparatus in accordance with claim 26 wherein each transmission means is located as close to the centre of gravity of the corresponding segment on said position reporting device as is practicable.

28. A method for positioning a movable position reporting device with a probe disposed on said movable position reporting device for determining data of an object comprising the following steps:

- a controller causes a driving means to generate a driving torque;
- said driving torque is applied to a movable member resulting in movement of said movable member;
- said movable member causes a force to be applied on a transmission means resulting in movement of said transmission means;
- said transmission means causes a force to be applied on a rigid part of said movable position reporting device resulting in movement of said movable position reporting device;
- said probe collects data of said object;
- a data processor receives a position from said position reporting device;
- said data processor receives said data from said probe.

29. A method for positioning a movable position reporting device with a probe disposed on said movable position reporting device for determining data of an object comprising the following steps:

- a controller causes a driving means to generate a driving torque;

- said driving torque is applied to a movable member resulting in movement of said movable me... er;
- said movable member causes a force to be applied on a transmission means resulting in movement of said transmission means;
- said transmission means causes a force to be applied on a rigid part of said movable position reporting device resulting in movement of said movable position reporting device;
- said probe collects synchronised data of said object and simultaneously sends a synchronisation signal to said position reporting device;
- a data processor receives a synchronised position from said position reporting device;
- said data processor receives said synchronised data from said probe.

30. A method for positioning a movable position reporting device with a probe disposed on said movable position reporting device for determining data of an object comprising the following steps:

- a controller causes a driving means to generate a driving torque;
- said driving torque is applied to a movable member resulting in movement of said movable member;
- said movable member causes a force to be applied on a transmission means resulting in movement of said transmission means;
- said transmission means causes a force to be applied on a rigid part of said movable position reporting device resulting in movement of said movable position reporting device;
- said probe collects data of said object time stamped by a clock in said probe;
- a data processor receives a position from said position reporting device time stamped by a clock in said position reporting device;
- said data processor receives said time stamped data from said probe.

ABSTRACT

ROBOT CMM ARM

Apparatus for a Robot CMM Arm is provided comprising an Internal CMM Arm, a base end of the Internal CMM Arm, a probe end of the Internal CMM Arm and a Robot Exoskeleton driving the Internal CMM Arm through a plurality of transmission means. A contact probe and an optical probe are mounted on the probe end of the Internal CMM Arm. The Robot CMM Arm is operable for automated and accurate measurement of an object. The user interface is provided by means of a laptop. Said Robot CMM Arm is operable in at least one manual teaching mode and at least one programmed measuring mode.

Refers to Figure 1C

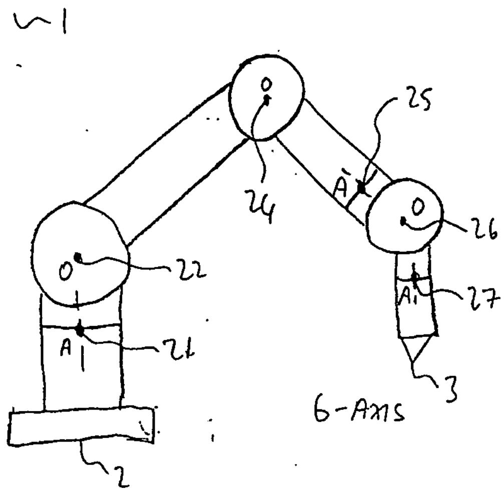


FIG. 1A

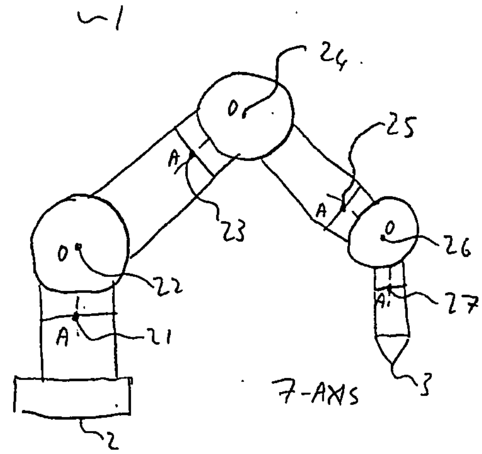


FIG. 1B

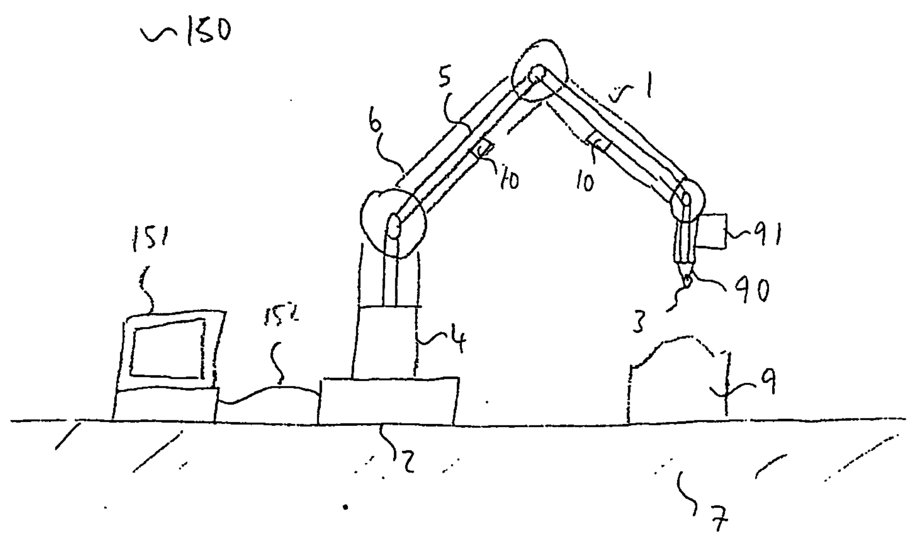


FIG. 1C

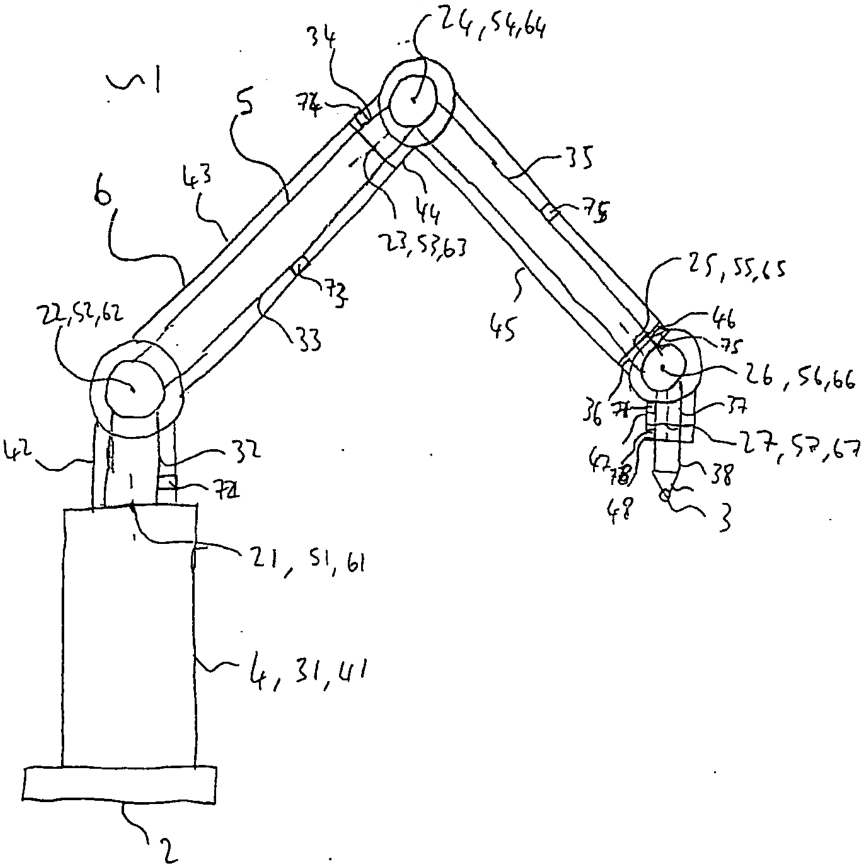

24,54,64
34
74
1
5
35
43
6
44
23,53,63
75
25,55,65
73
45
46
22,52,62
33
75
26,56,66
36
77
37
42
32
27,57,67
47
78
38
72
48
3
21, 51, 61
4, 31, 41
2

FIG. 2

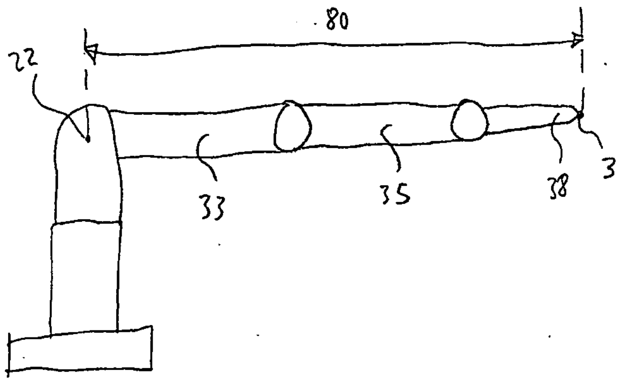


FIG. 3

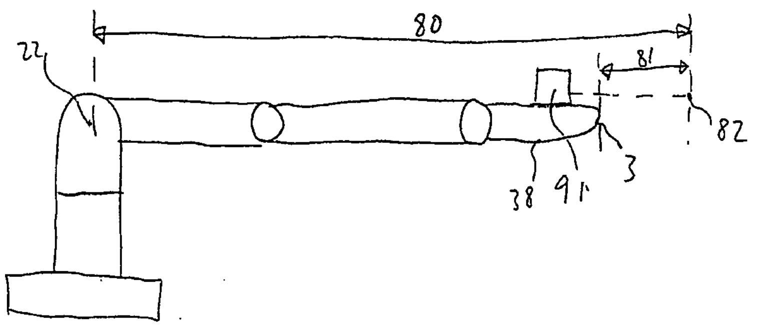


FIG. 4

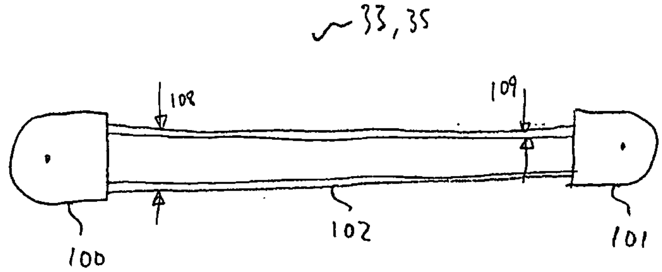


FIG. 5A

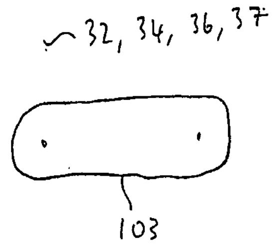


FIG. 5B

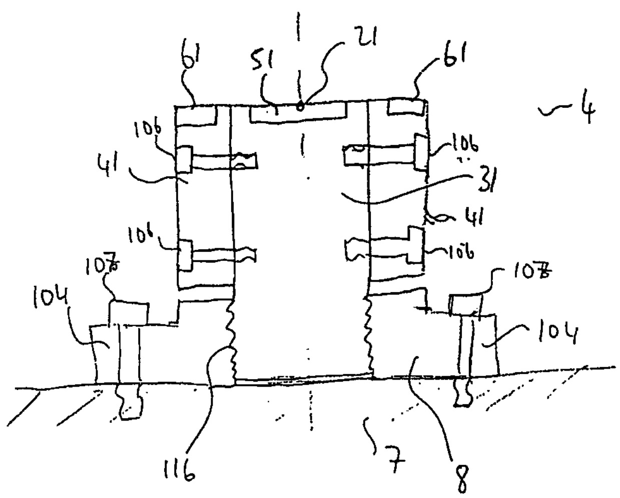


FIG 5D

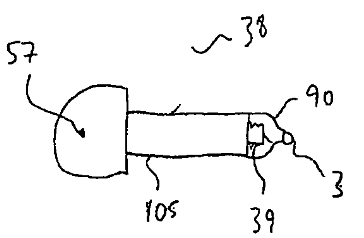
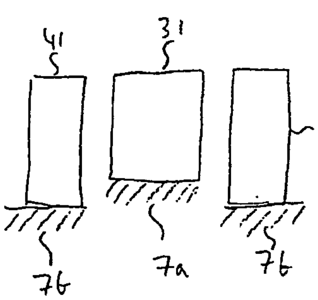
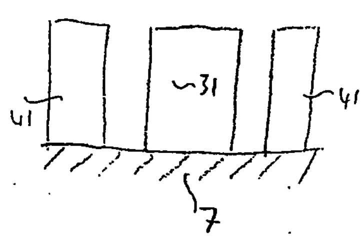


FIG. 5C





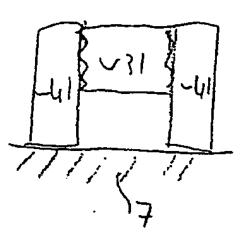


FIG 5E

FIG. 5F

FIG 5G

FIG 5H

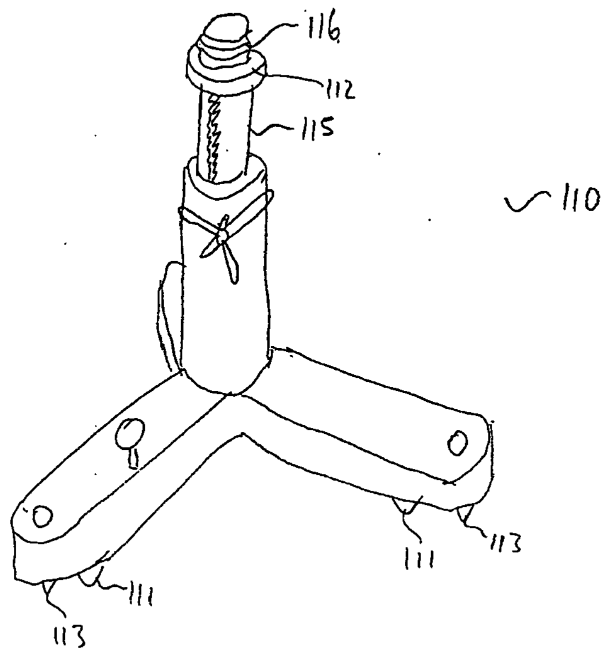


FIG 6

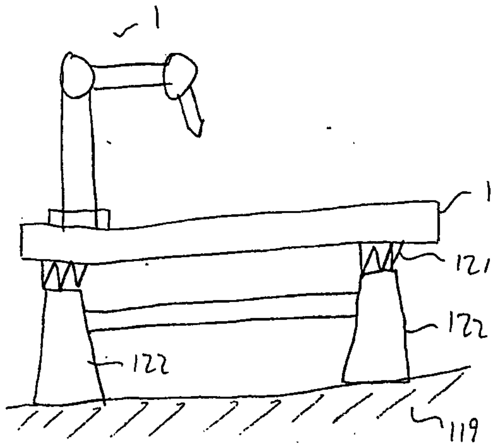


FIG. 7A

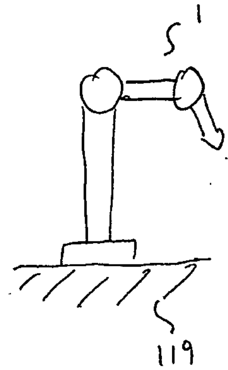


FIG. 7B

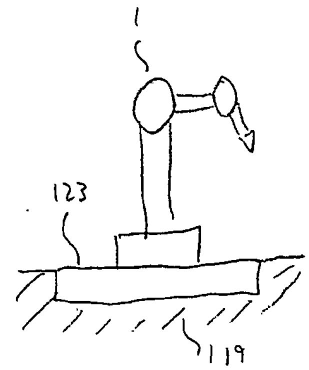


FIG. 7C

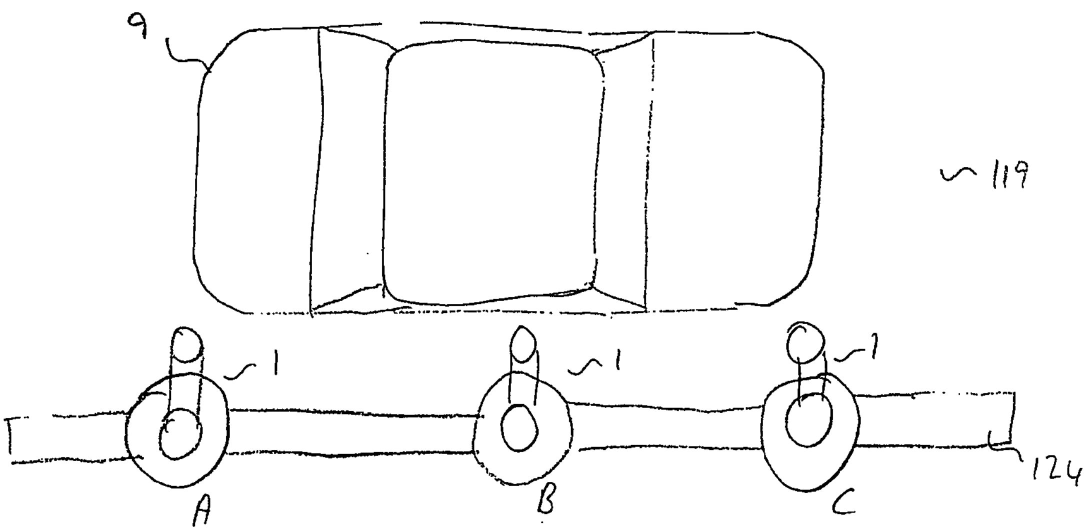


FIG. 7D

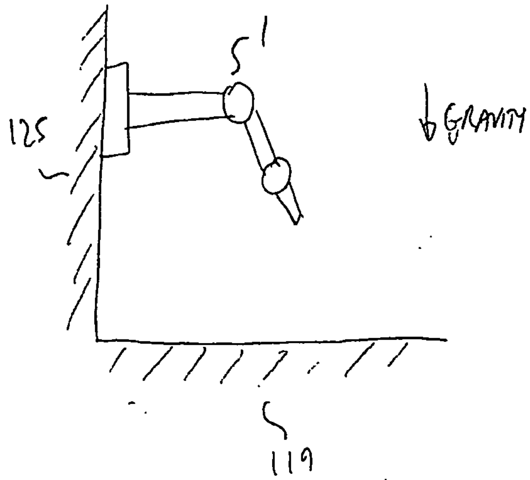


FIG. 8A

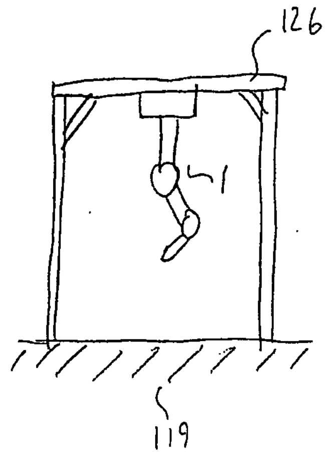


FIG. 8B

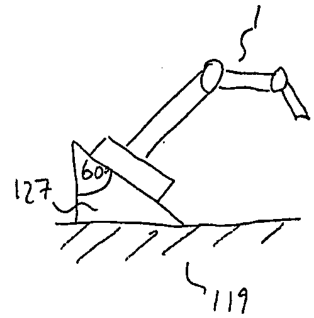


FIG 8C

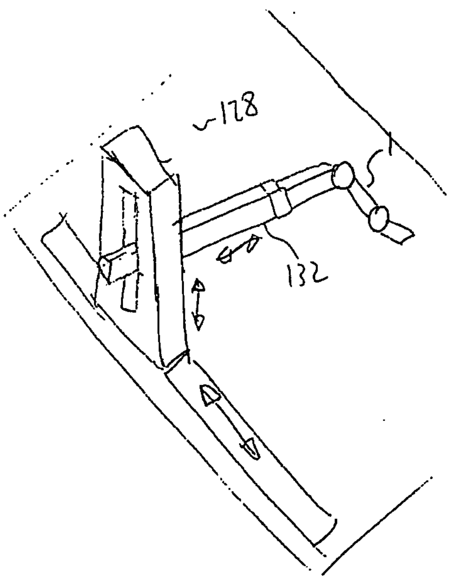


FIG 8D

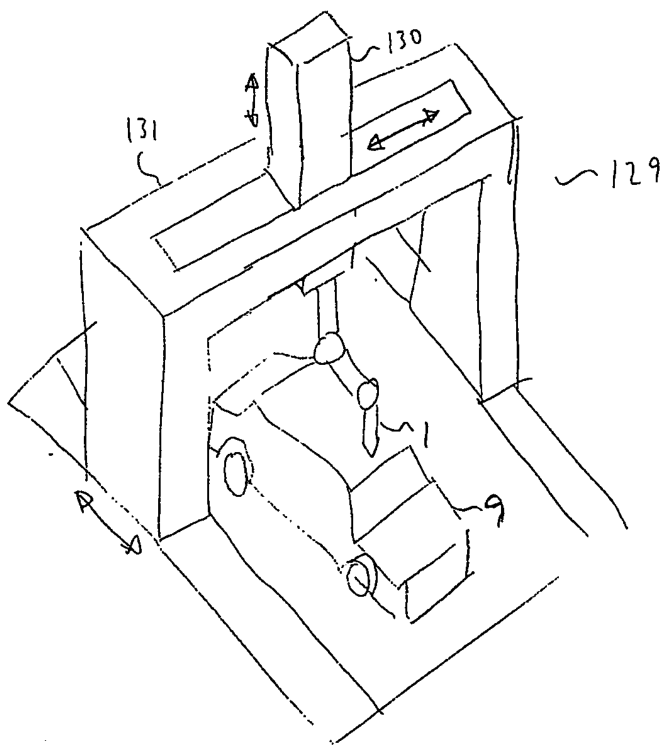


FIG. 8E

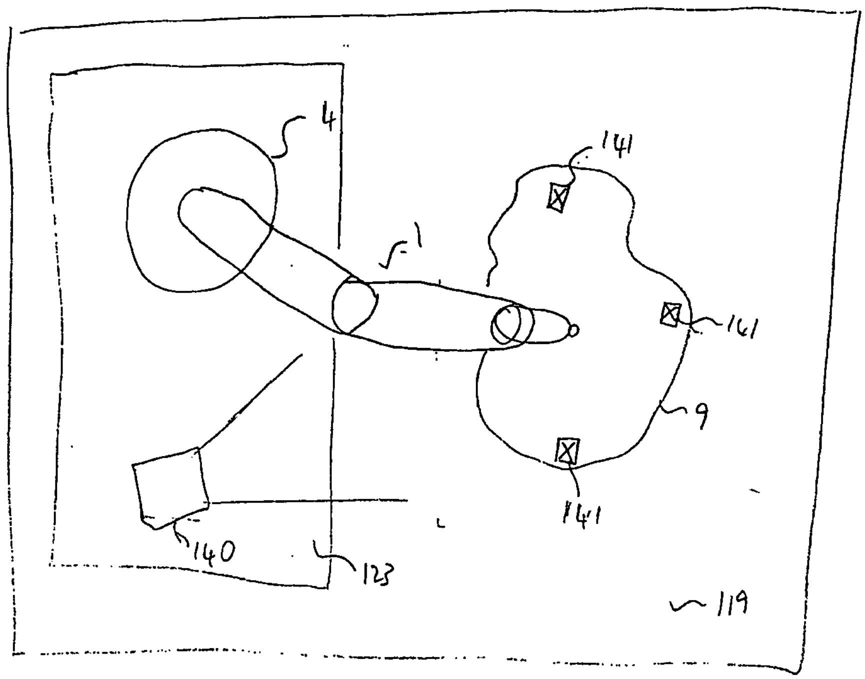


FIG. 9

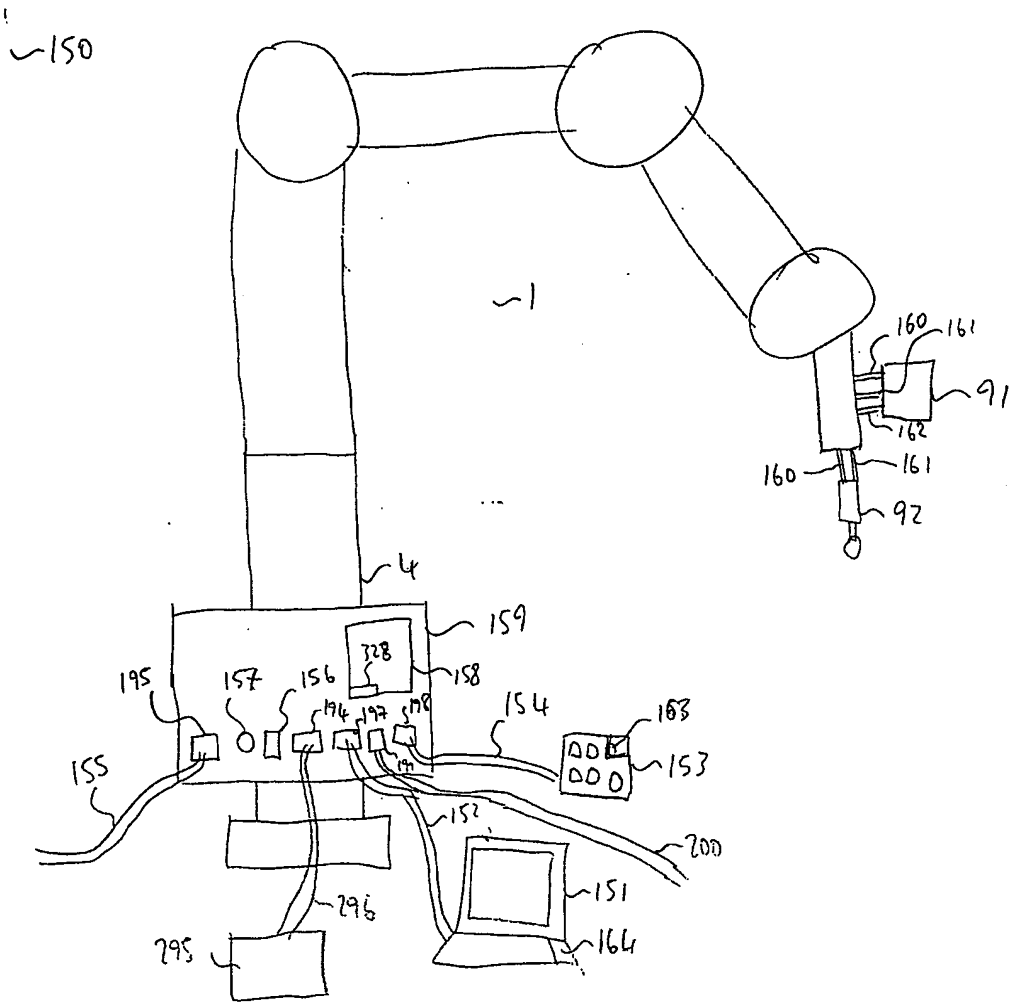

150
1
160
161
91
162
160
161
92
4
159
328
158
195
157
156
194
197
198
154
183
153
155
199
152
200
151
296
164
295

FIG. 10

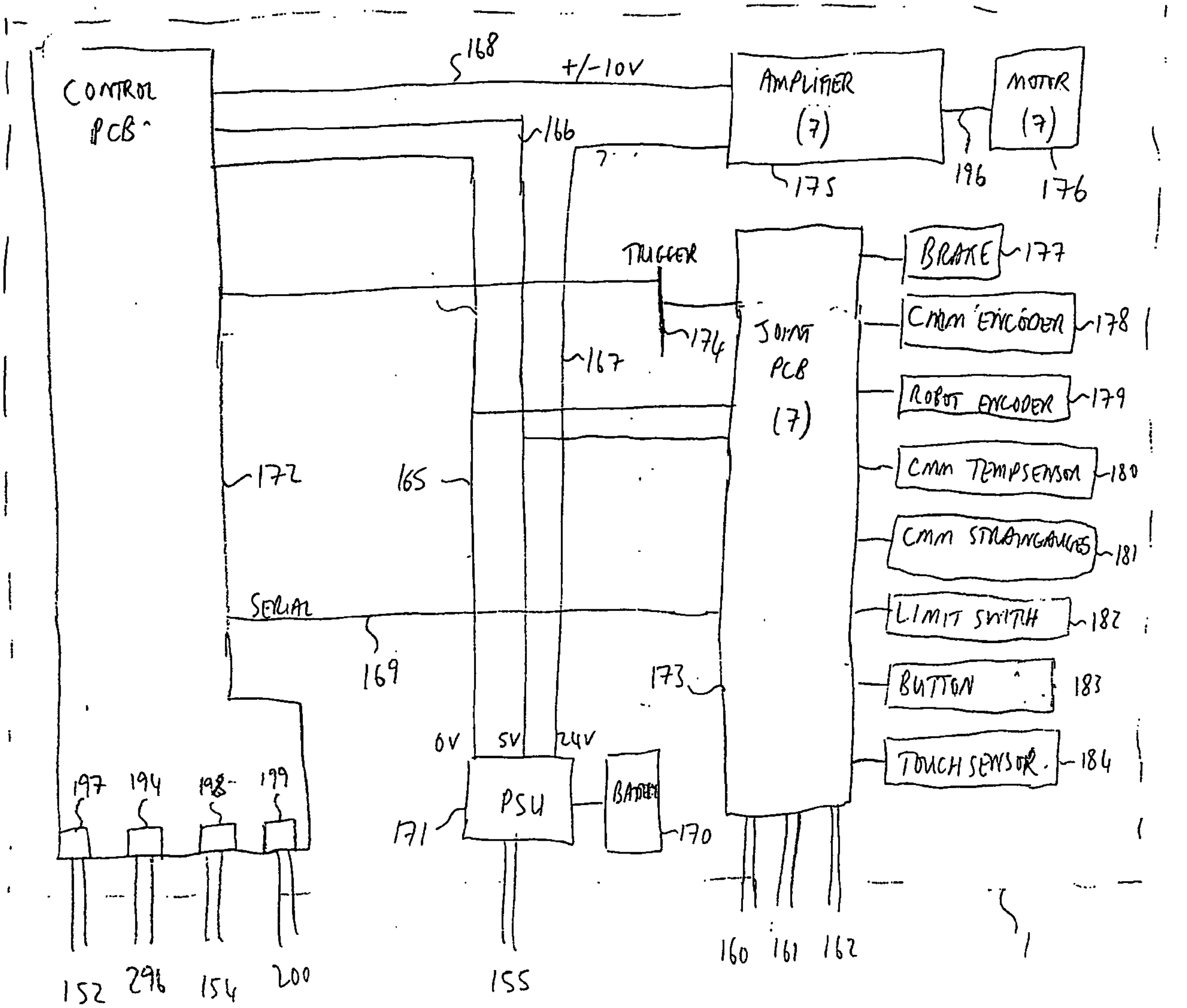

CONTROL PCB
168
+/-10V
AMPLIFIER (7)
MOTOR (7)
166
175
196
176
TRIGGER
BRAKE
177
CMM ENCODER
178
JOINT PCB (7)
174
167
ROBOT ENCODER
179
CMM TEMPSENSOR
180
172
165
CMM STRAINGAUGES
181
SERIAL
LIMIT SWITCH
182
169
173
BUTTON
183
0V
5V
24V
TOUCH SENSOR
184
197
194
198
199
PSU
BATTERY
171
170
160
161
162
152
296
154
200
155
1

FIG. 11

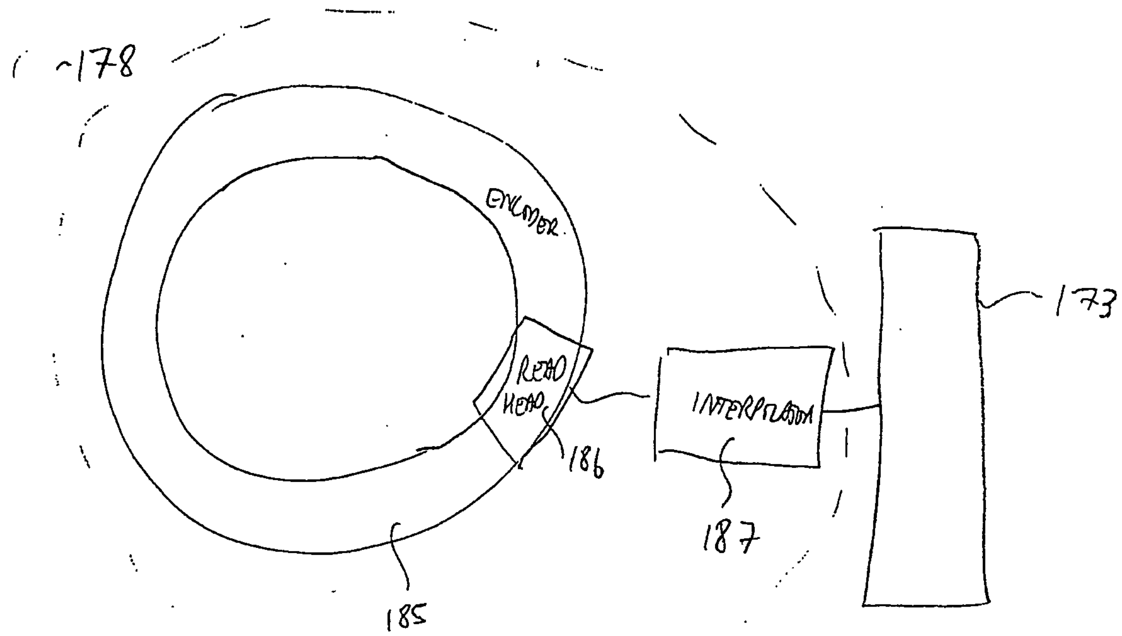

~178
ENCODER
READ HEAD
186
INTERPOLATION
173
187
185

FIG. 12

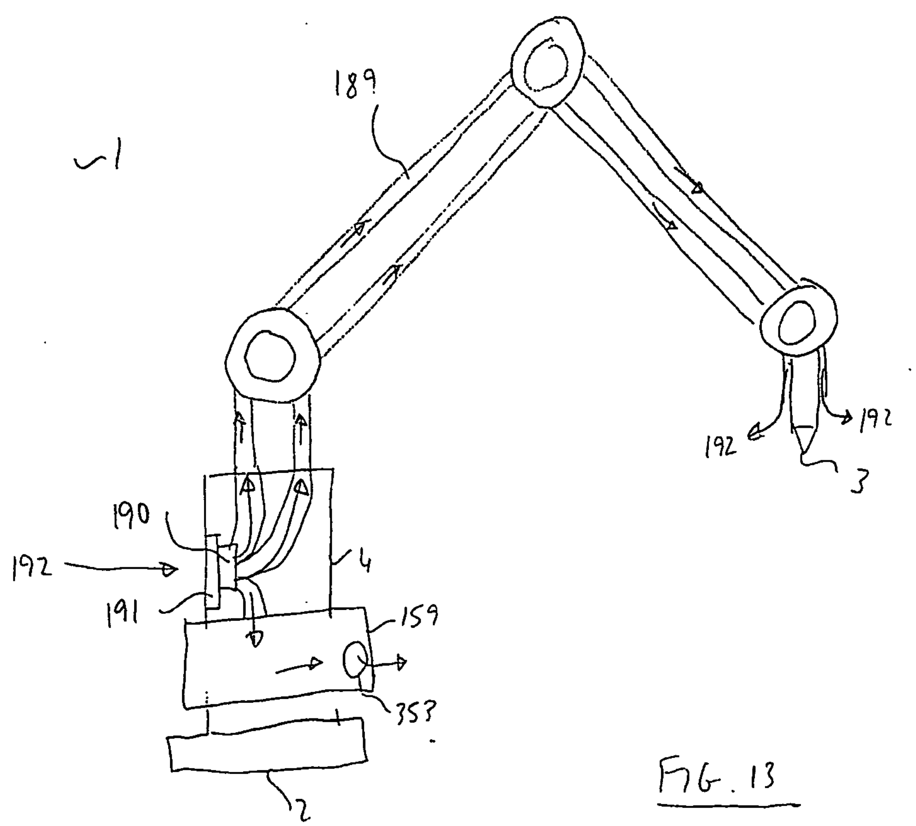

189
~1
192
192
3
190
192
4
191
159
353
2

FIG. 13

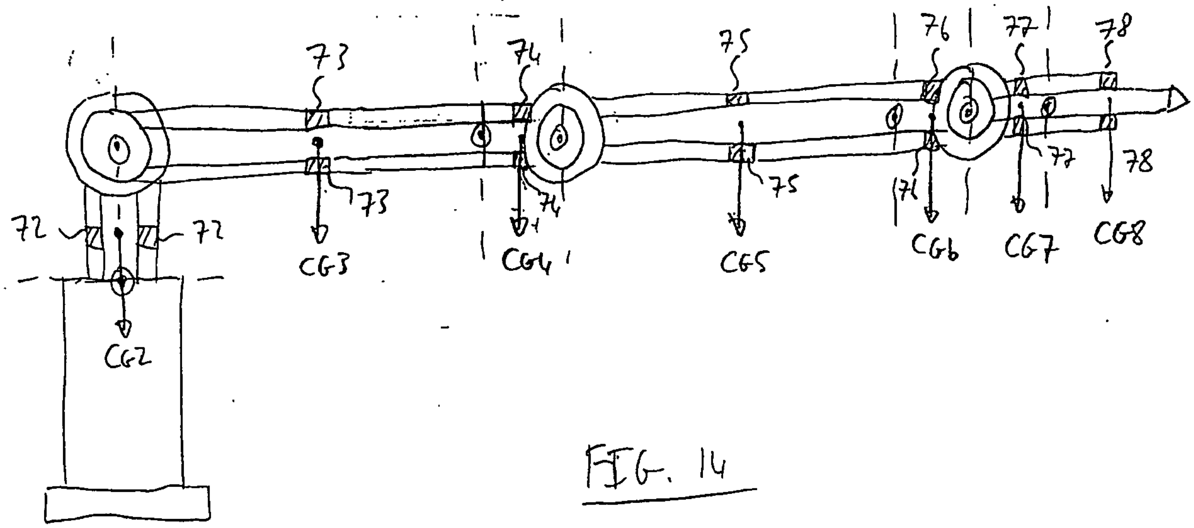

73
74
75
76
77
78
72
72
73
74
75
76
77
78
CG2
CG3
CG4
CG5
CG6
CG7
CG8

FIG. 14

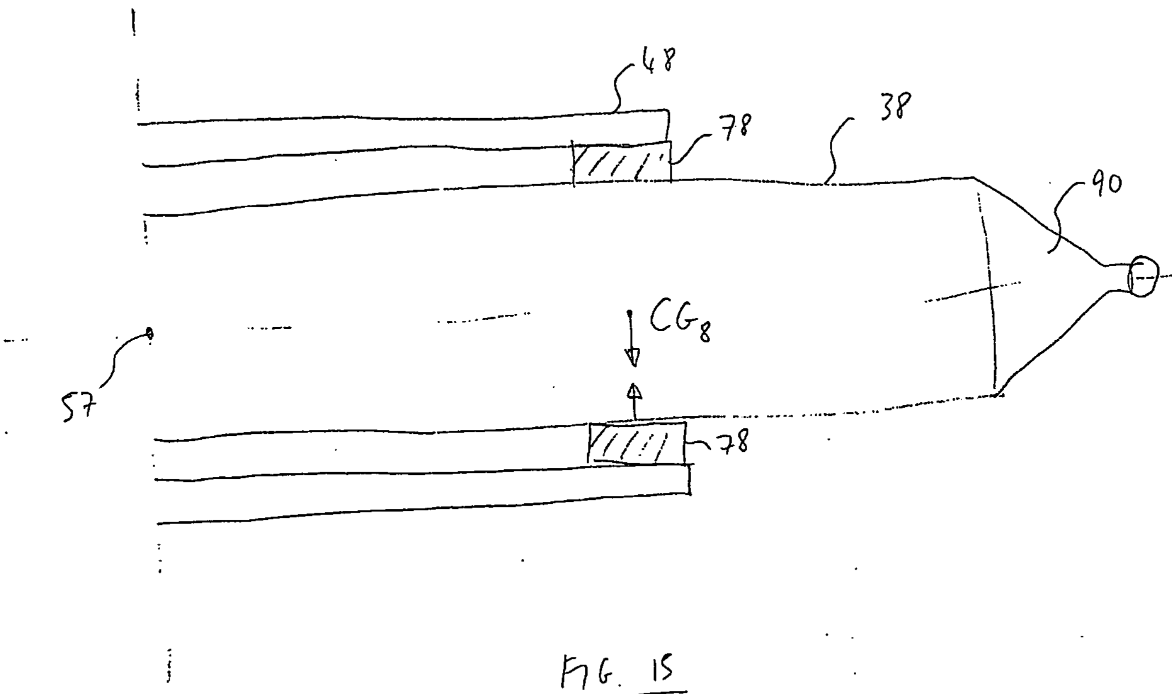

48
78
38
90
CG_8
57
78

FIG. 15

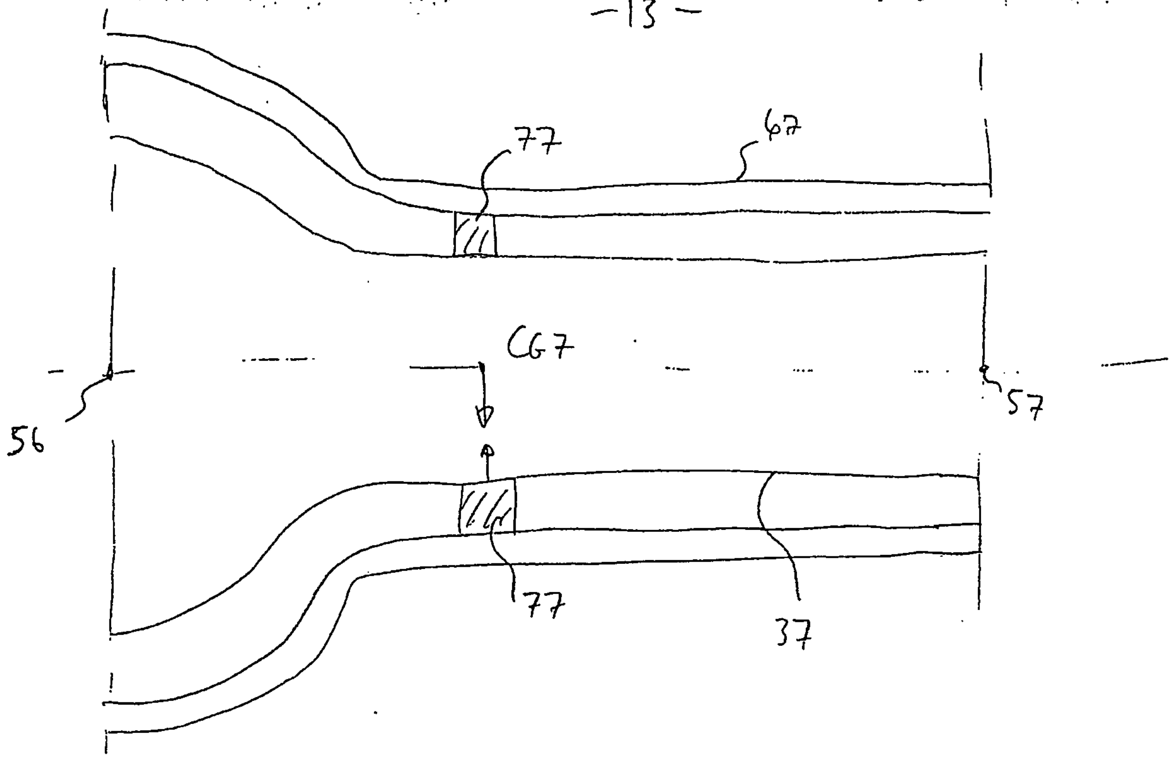


FIG. 16

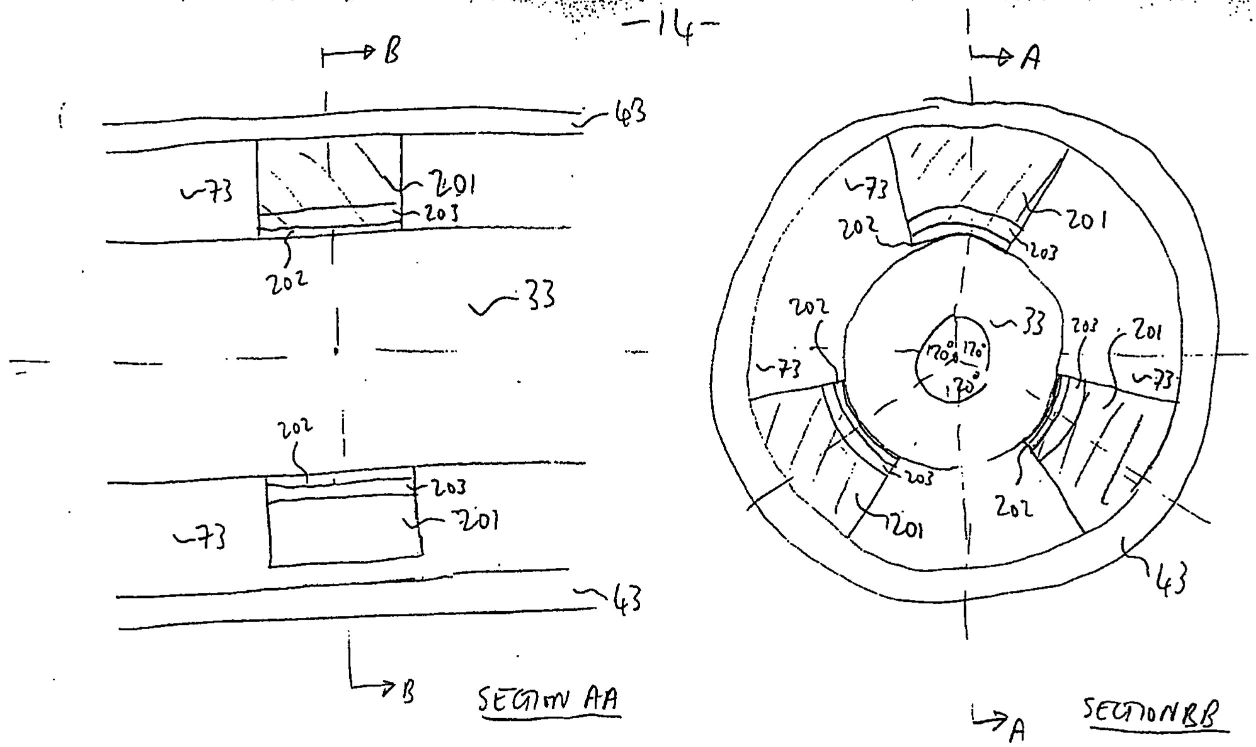

B
43
73
201
203
202
33
202
203
201
73
43
B
SECTION AA
A
73
201
202
203
202
33
120°
120°
120°
203
201
73
73
203
201
202
43
A
SECTION BB

FIG. 17

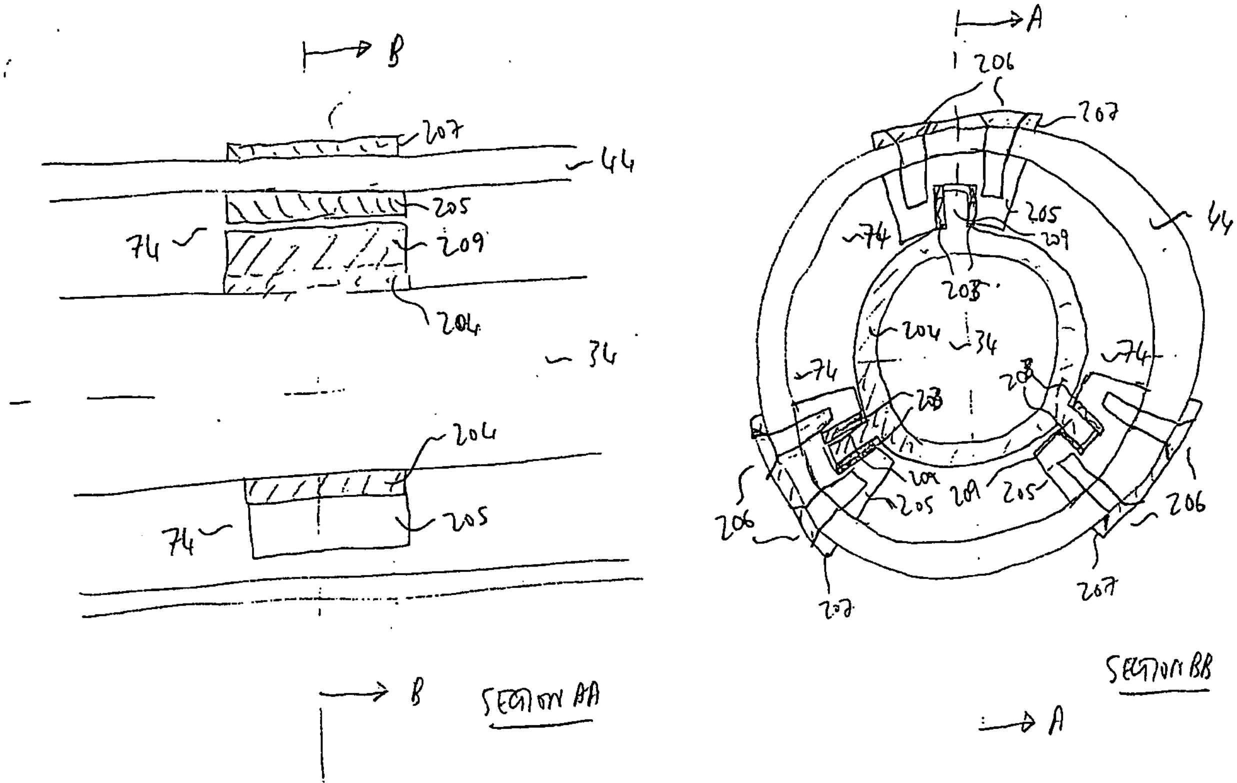

B
207
44
205
74
209
204
34
204
74
205
B
SECTION AA
A
206
207
205
209
74
44
208
204
34
74
74
208
208
209
205
209
205
206
206
207
207
SECTION BB
A

FIG. 18

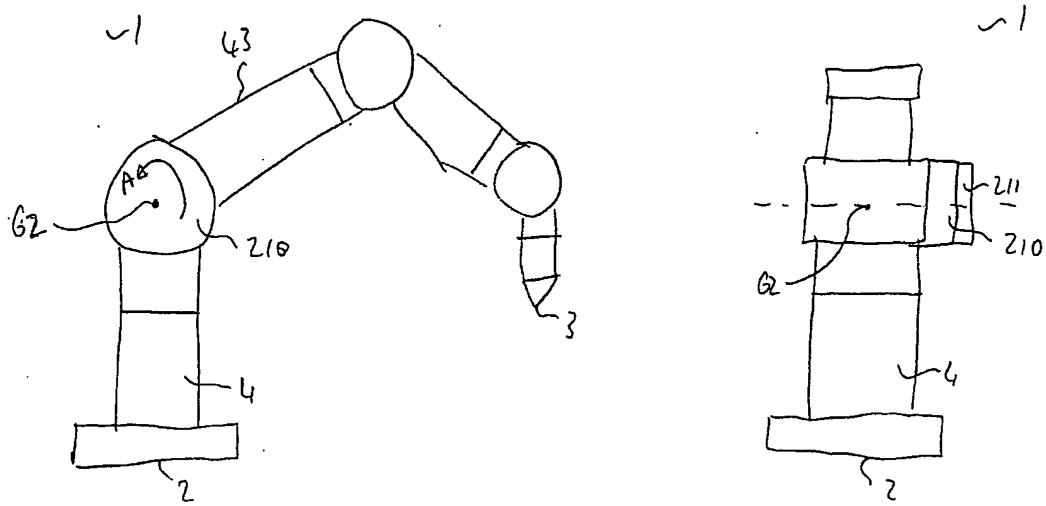


FIG. 19

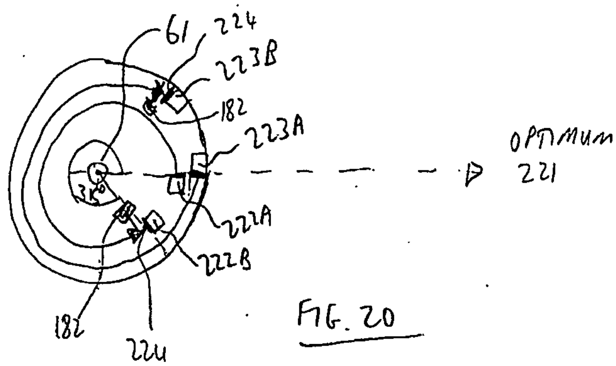


FIG. 20

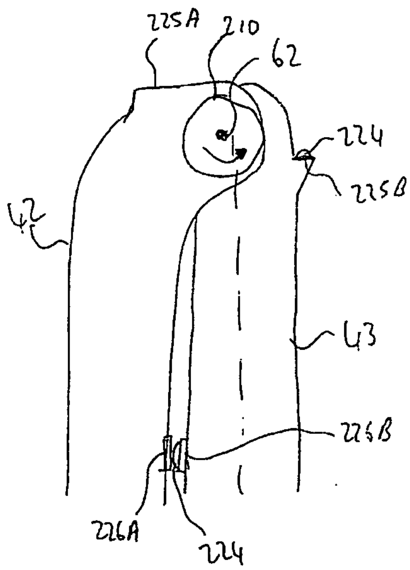


FIG. 21A

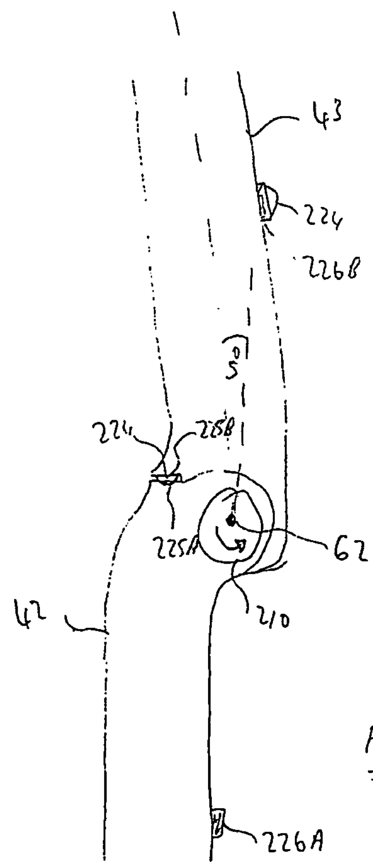


FIG 21B

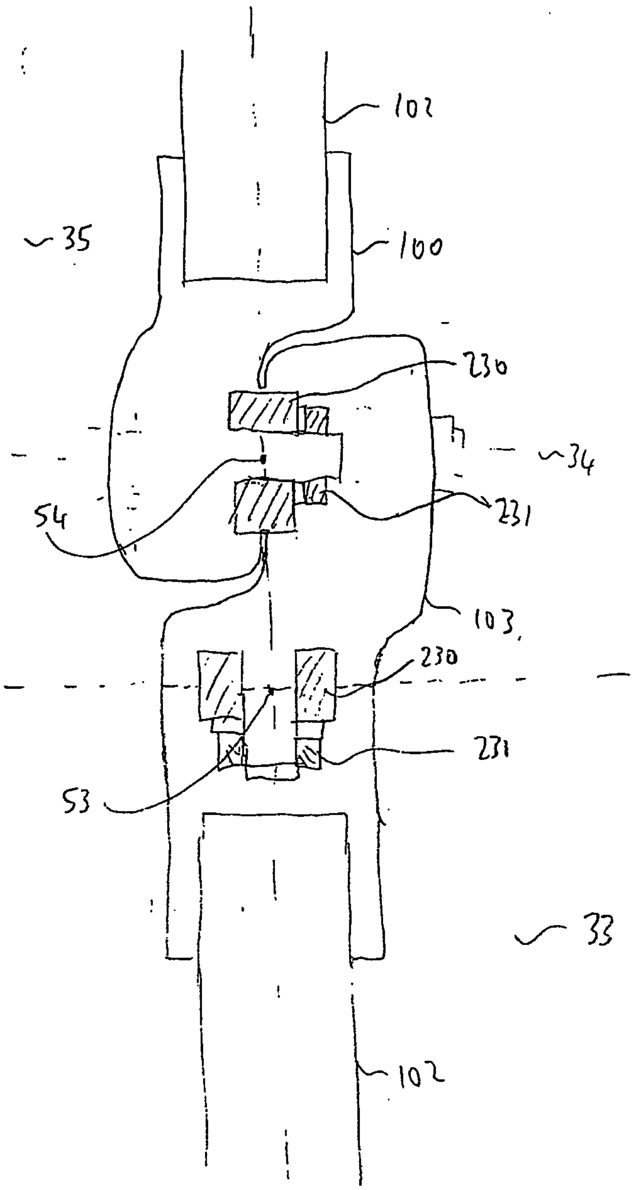


FIG. 22

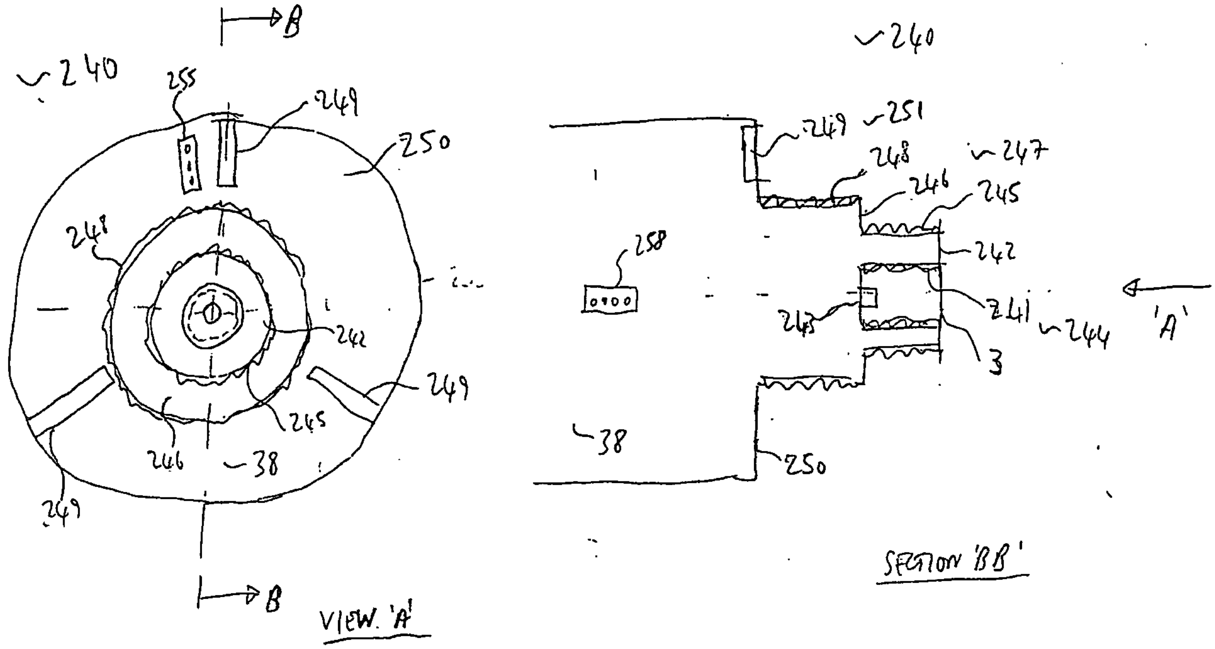


FIG. 23

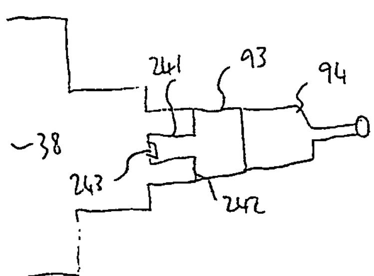


FIG. 24

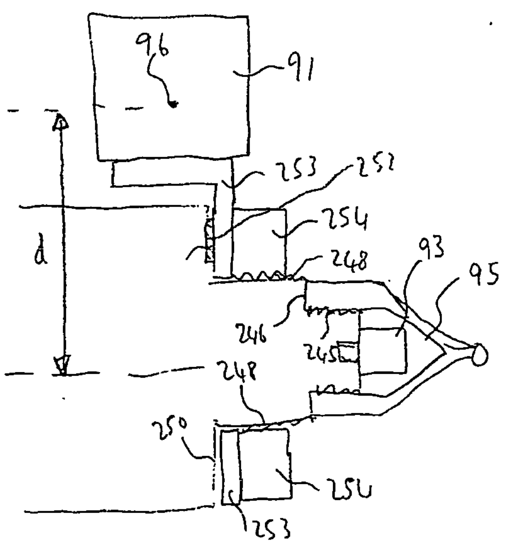


FIG 25

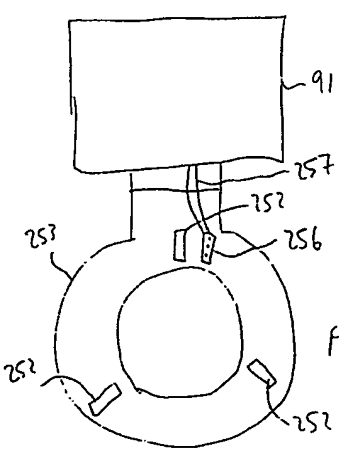


FIG. 26

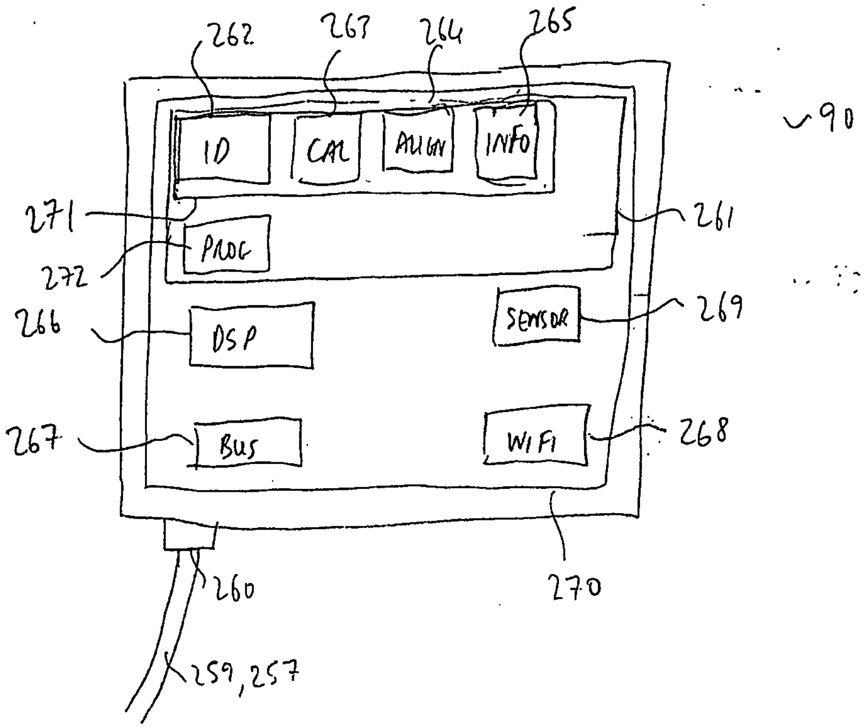


FIG. 27A

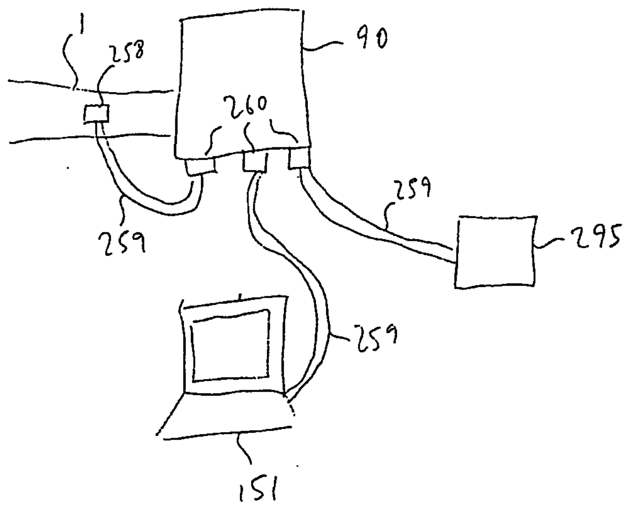


FIG. 27B

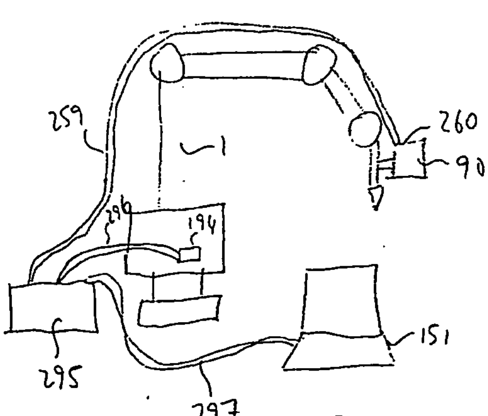


FIG. 27C

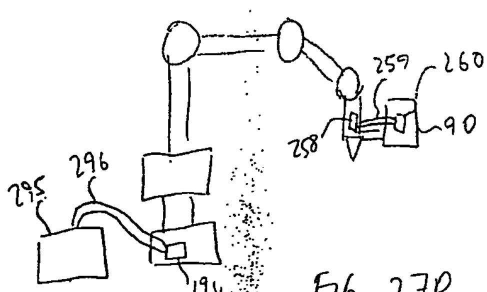


FIG. 27D

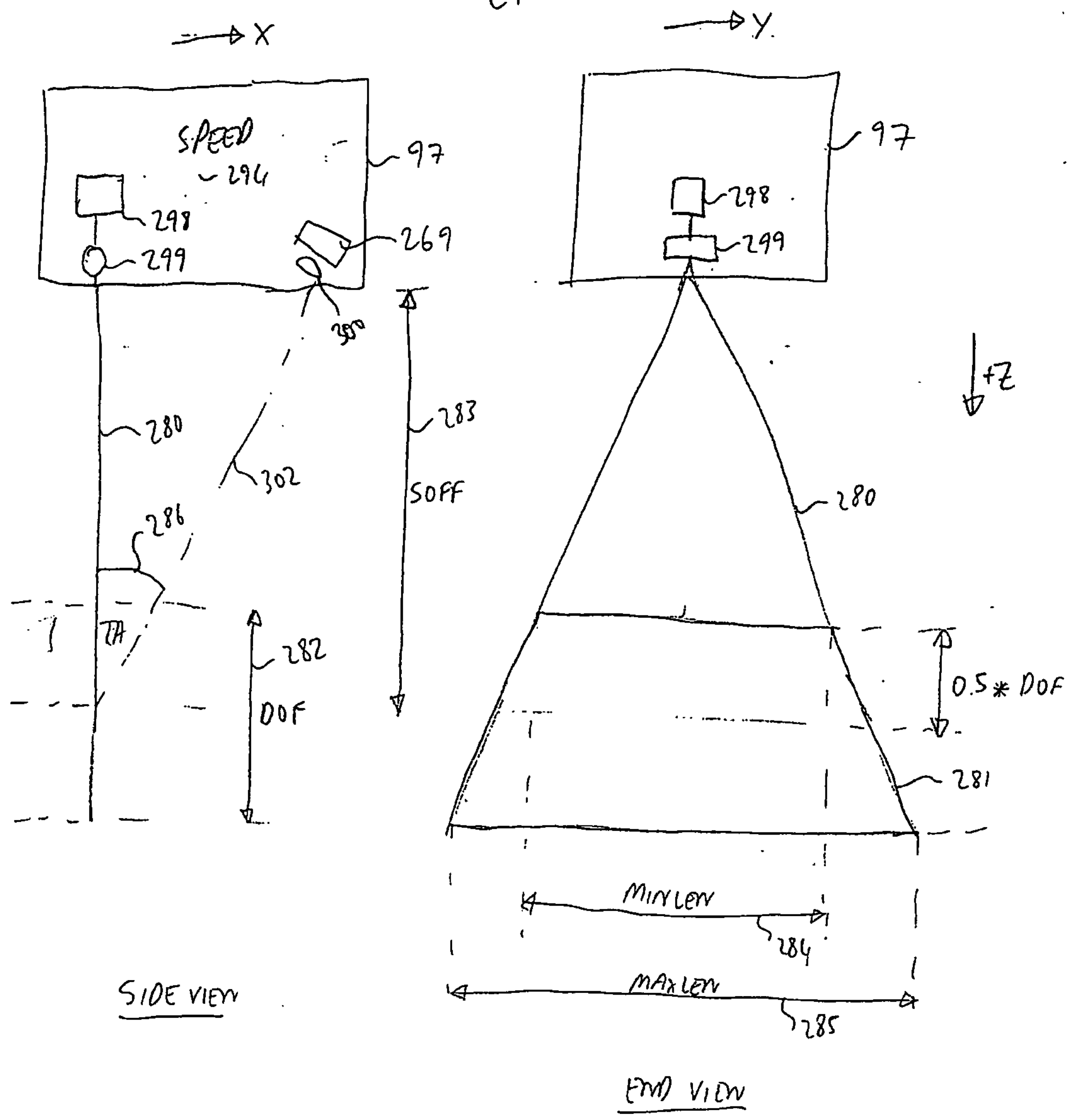

X
Y
SPEED
294
97
298
299
269
300
283
SOFF
280
302
286
TH
282
DOF
+Z
0.5 * DOF
281
MIN LEN
284
MAX LEN
285
SIDE VIEW
END VIEW

FIG. 28

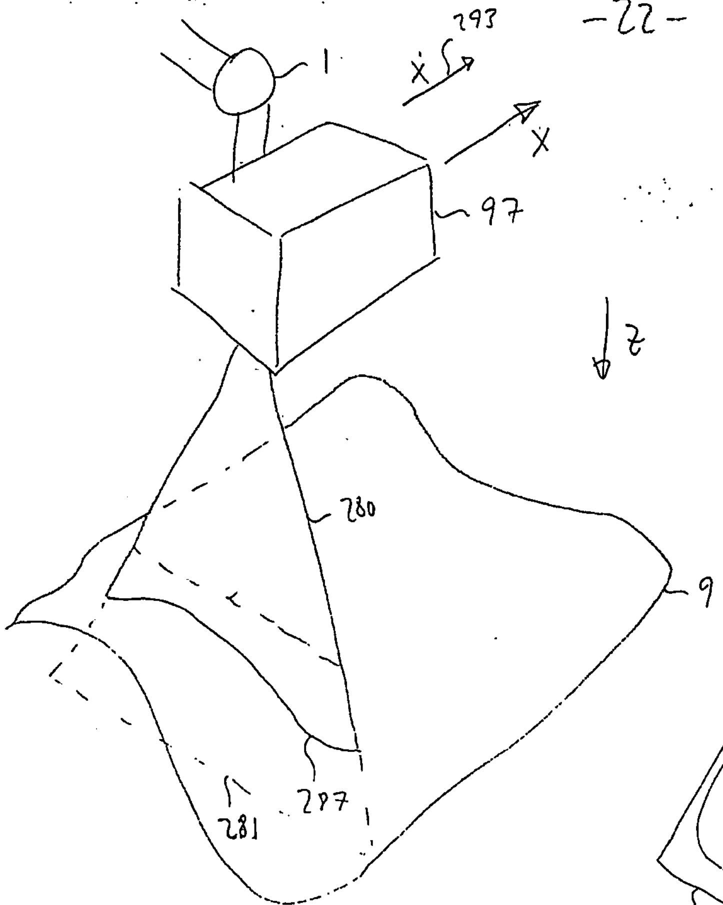


FIG 29

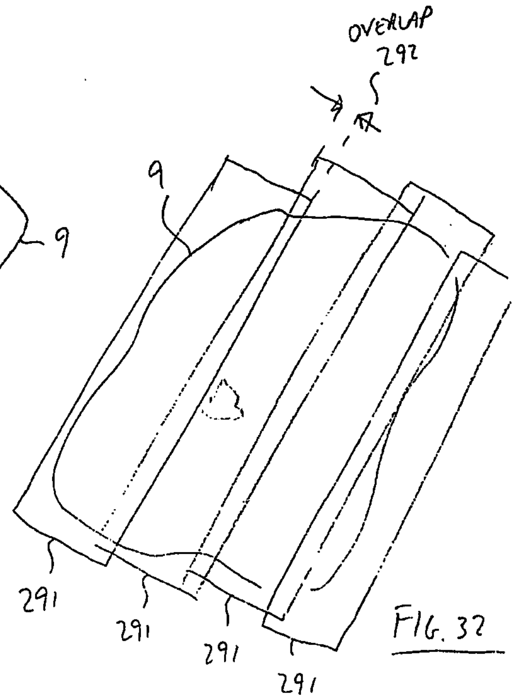


FIG. 32

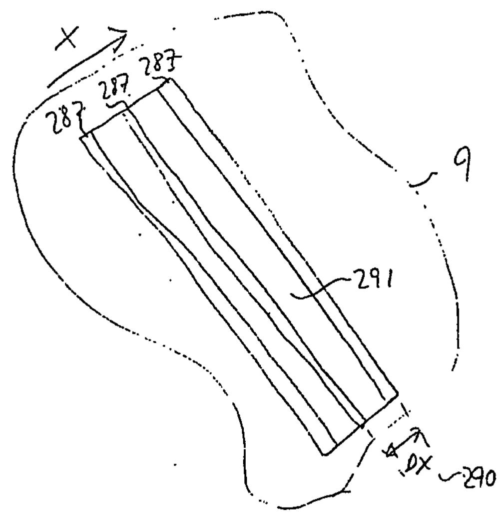


FIG 31

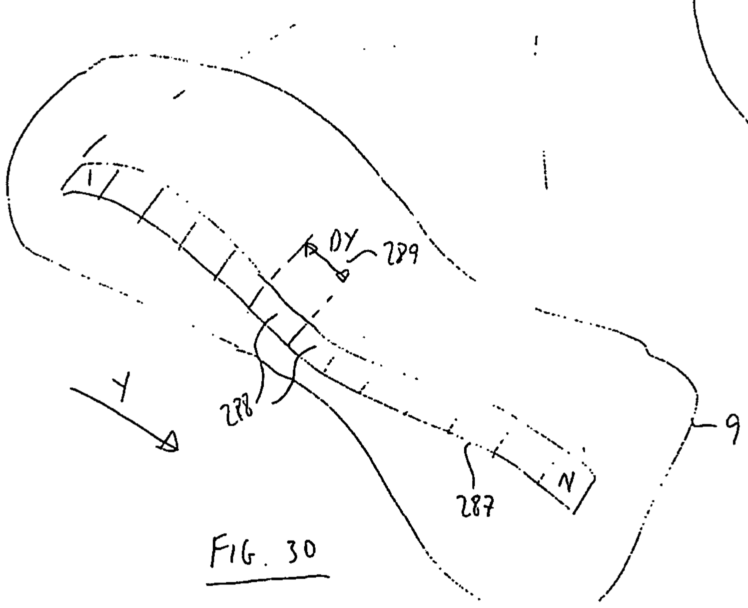
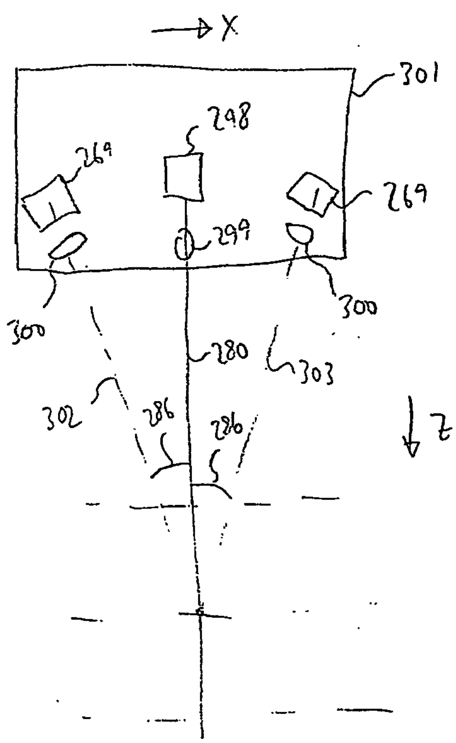


FIG. 30



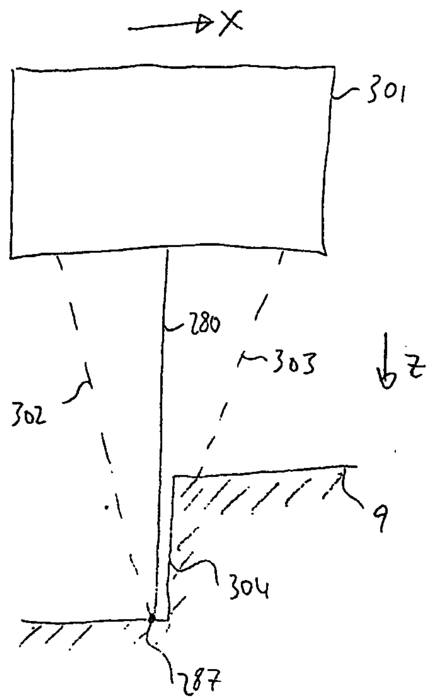
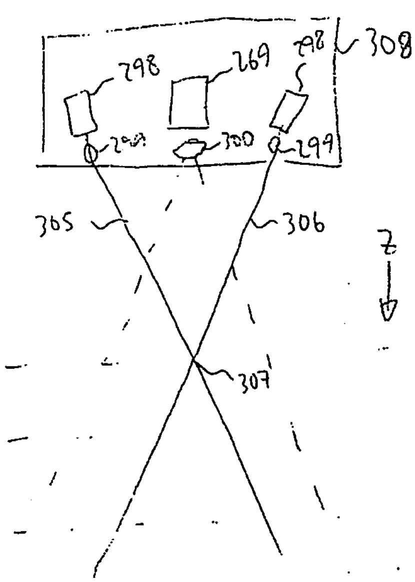


FIG. 33B

FIG. 33A



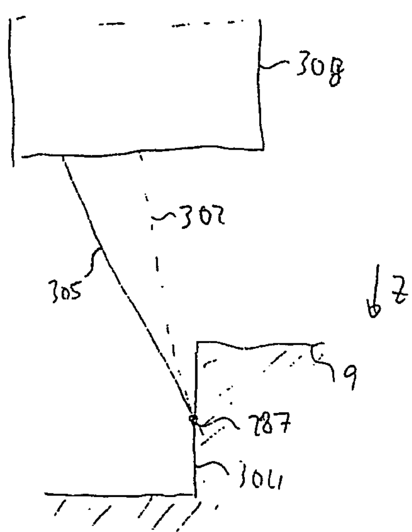


FIG. 34A

FIG. 34B

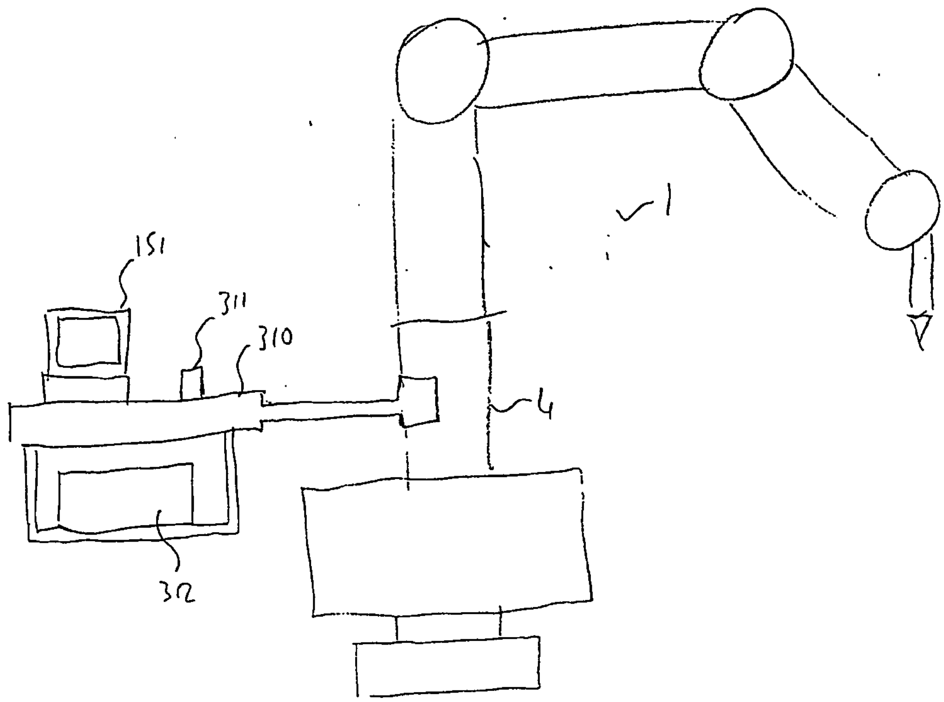


FIG 35

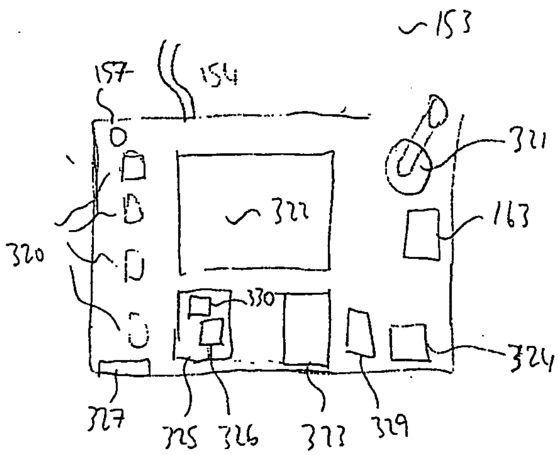


FIG. 36

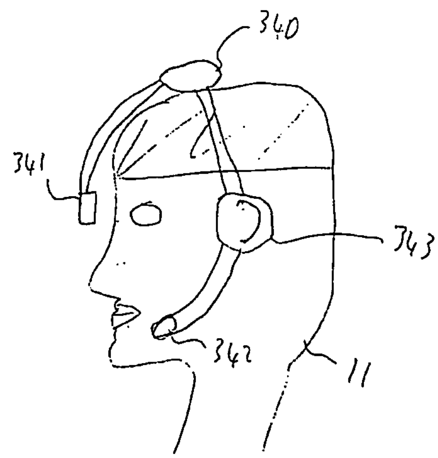


FIG. 37

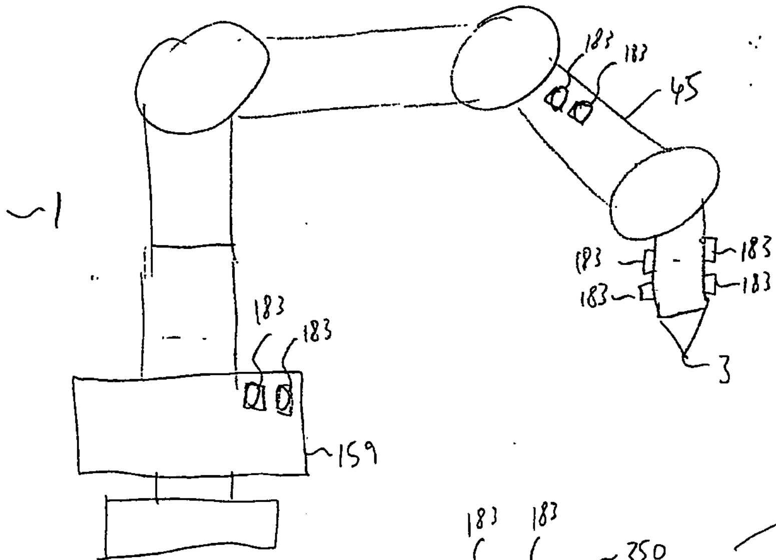


FIG. 38A

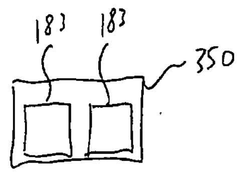


FIG. 38B

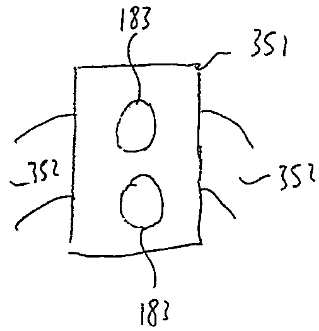


FIG. 38C

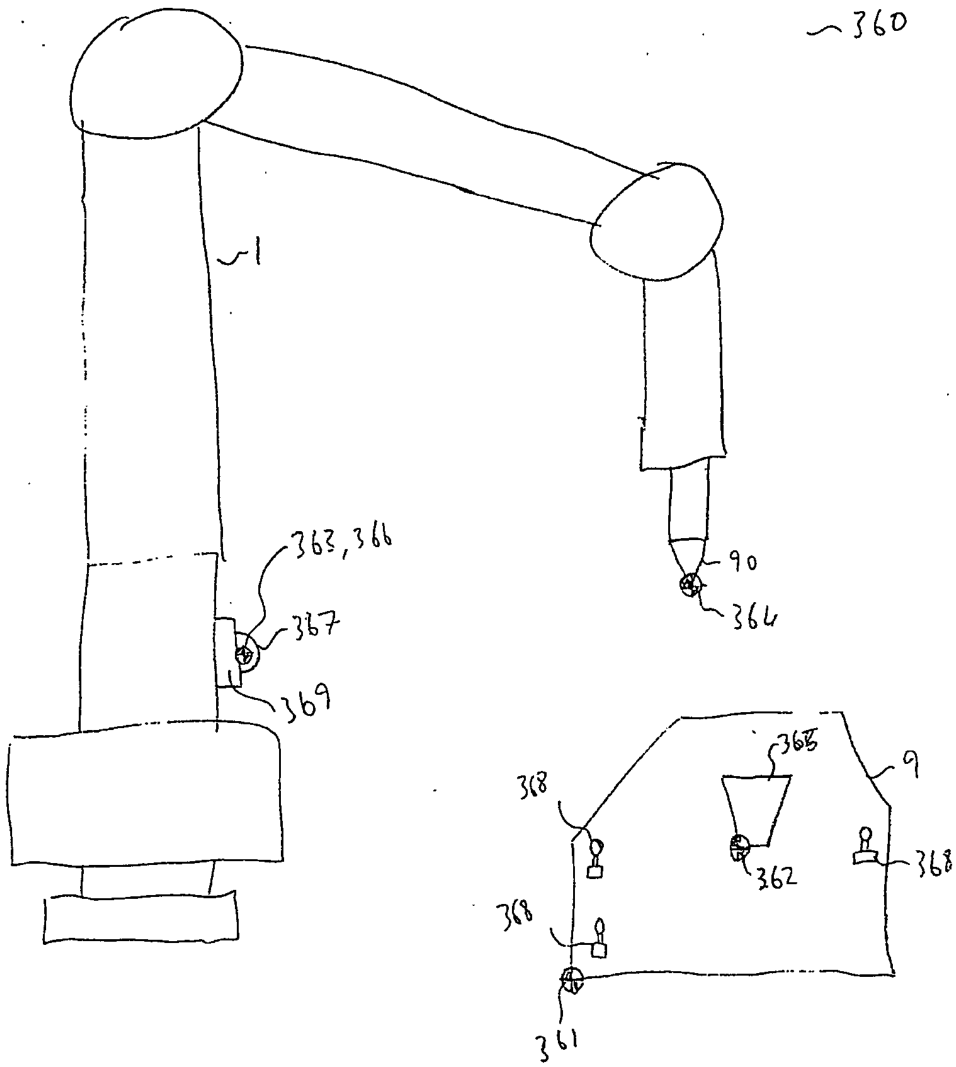


FIG. 39

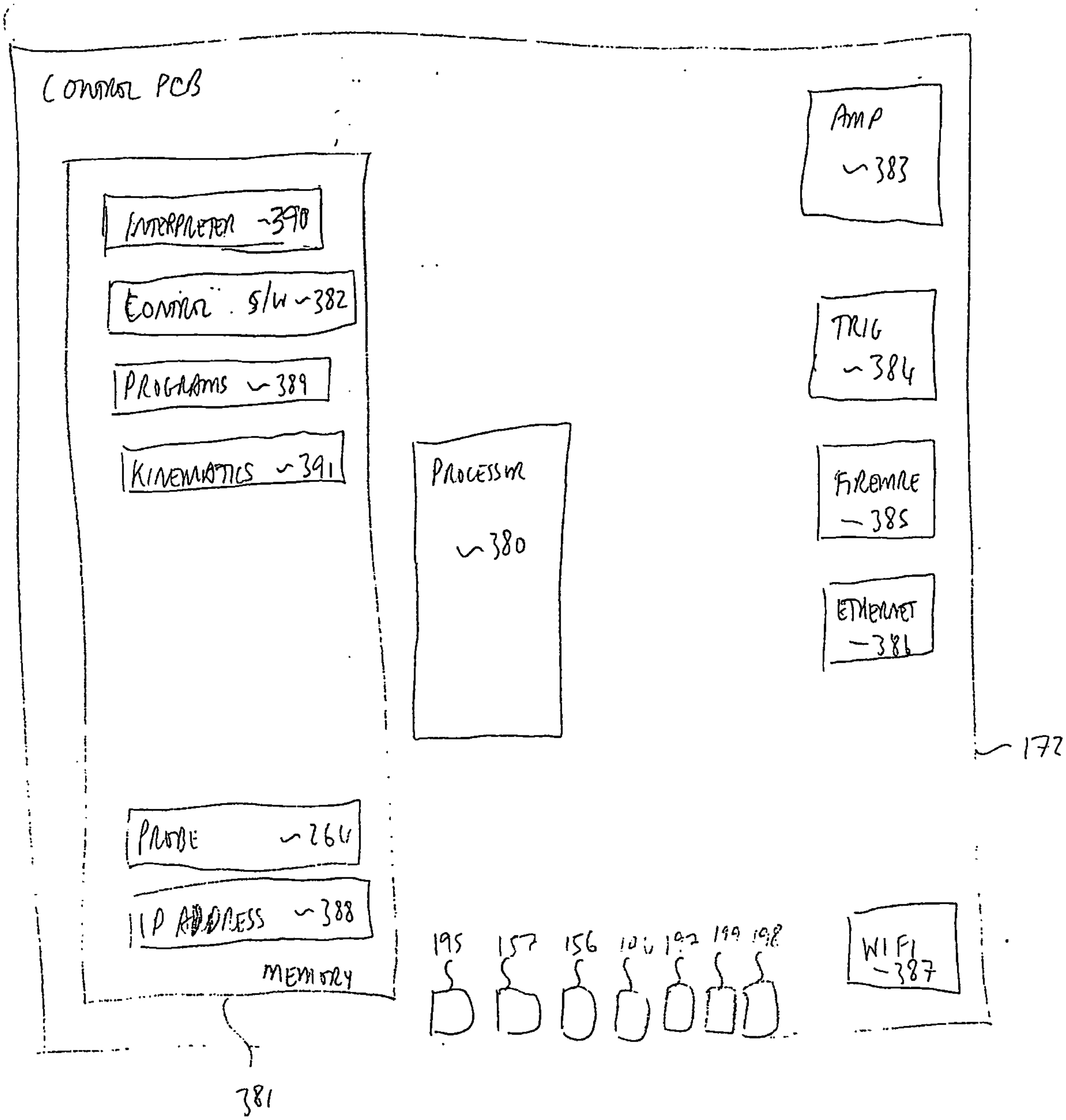

CONTROL PCB
INTERPRETER ~390
CONTROL S/W ~382
PROGRAMS ~389
KINEMATICS ~391
PROBE ~264
IP ADDRESS ~388
MEMORY
381
PROCESSOR
~380
AMP
~383
TRIG
~384
FIREWIRE
~385
ETHERNET
~386
WIFI
~387
195
157
156
172

FIG. 40

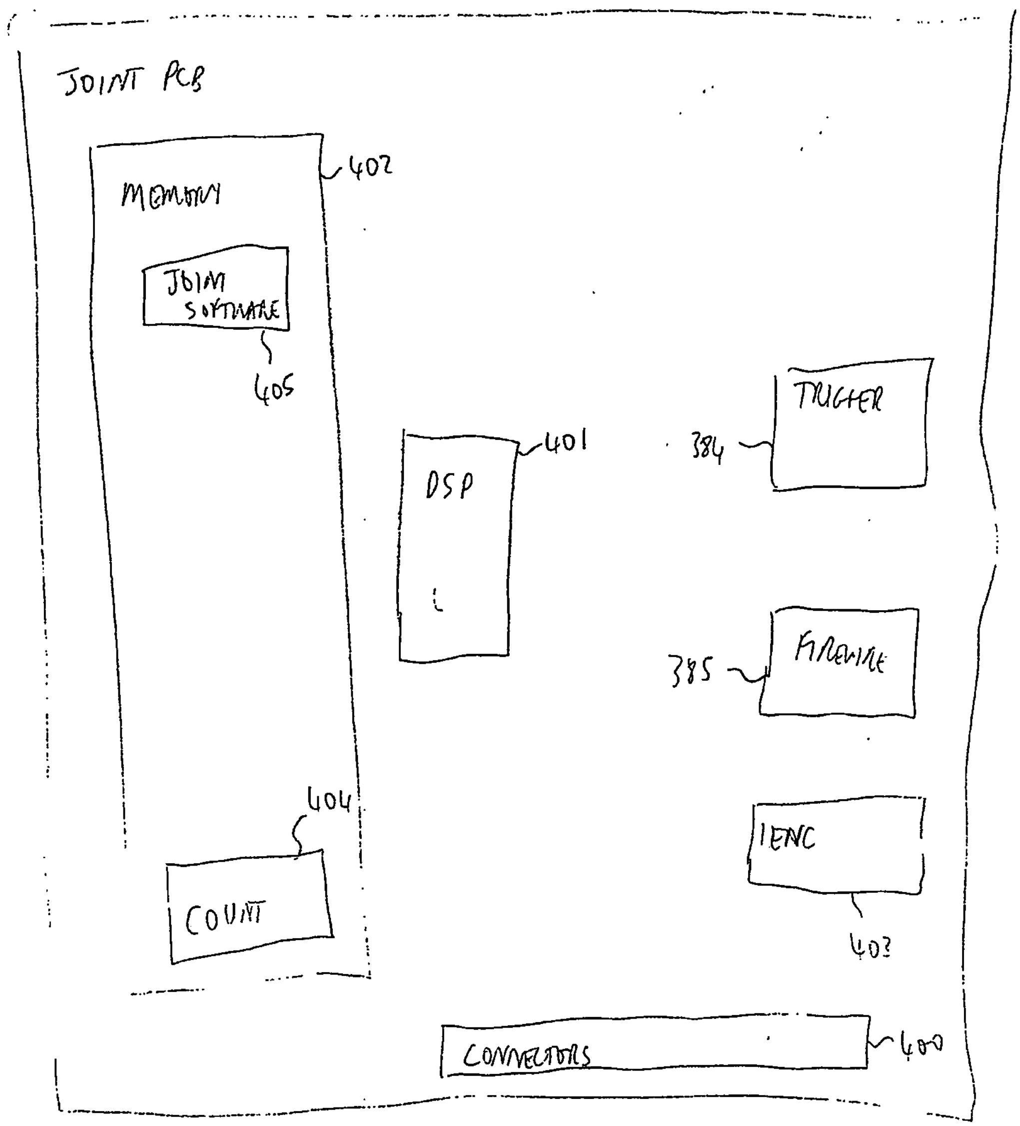

JOINT PCB
MEMORY
402
JOINT SOFTWARE
405
DSP
401
384
TRIGGER
385
FIREWIRE
404
COUNT
IENC
403
CONNECTORS
400

FIG. 41

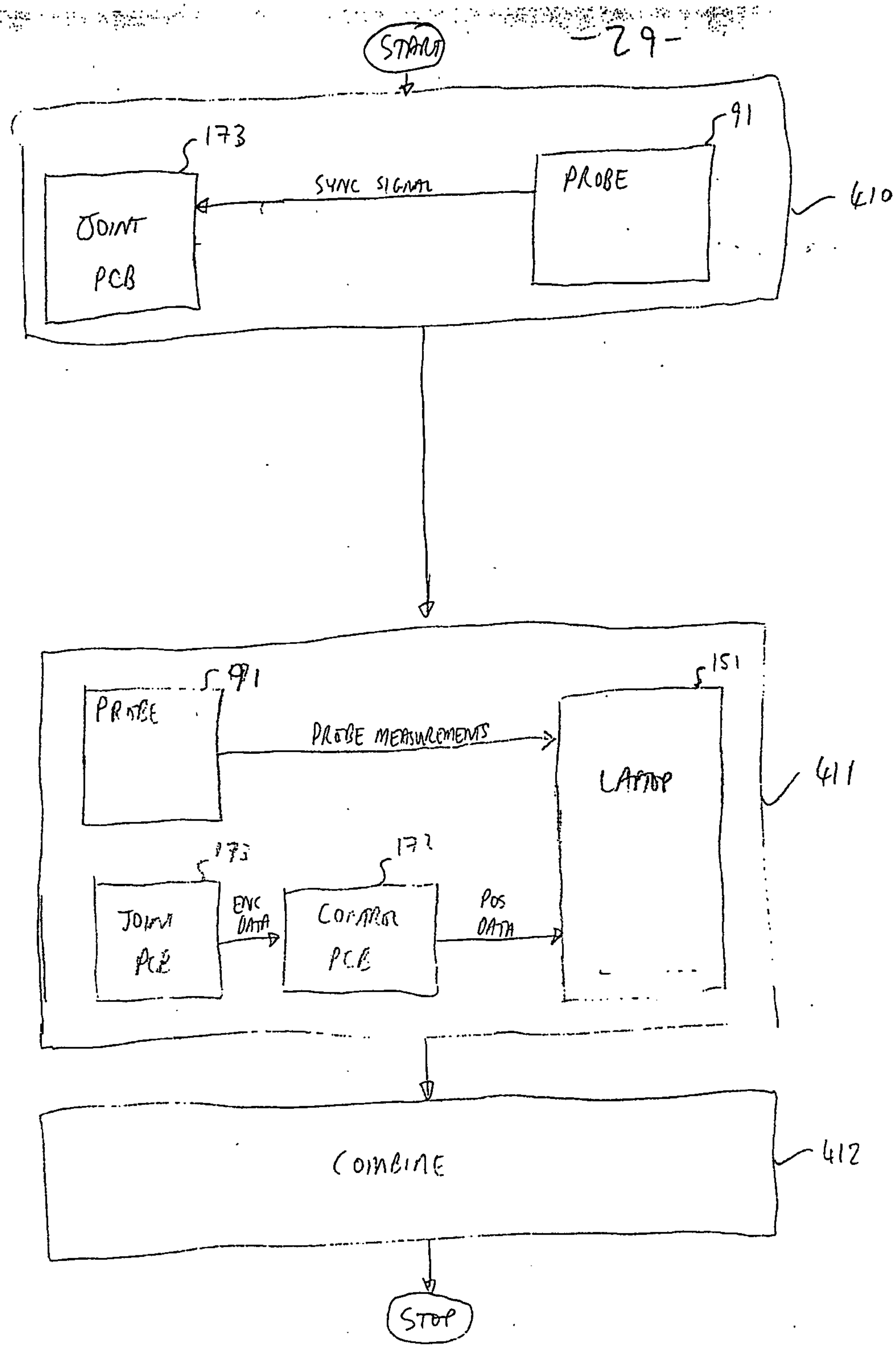

START
173
91
SYNC SIGNAL
JOINT PCB
PROBE
410
91
151
PROBE
PROBE MEASUREMENTS
LAPTOP
411
173
172
JOINT PCB
ENC DATA
CONTROL PCB
POS DATA
COMBINE
412
STOP

FIG. 42

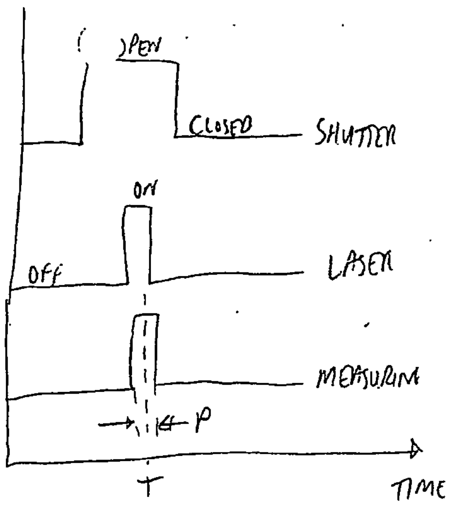


FIG. 63A

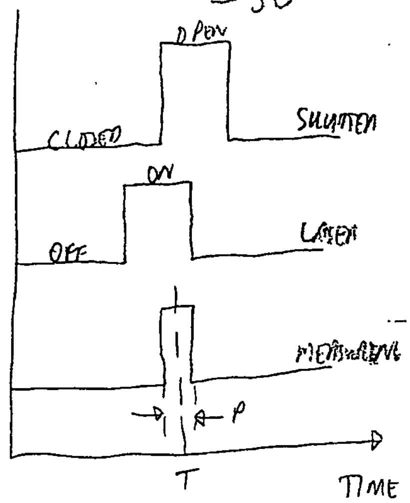


FIG. 63B

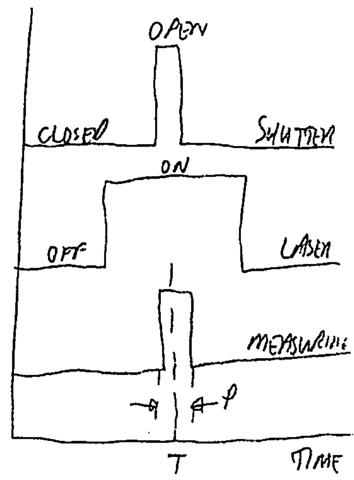


FIG. 63C

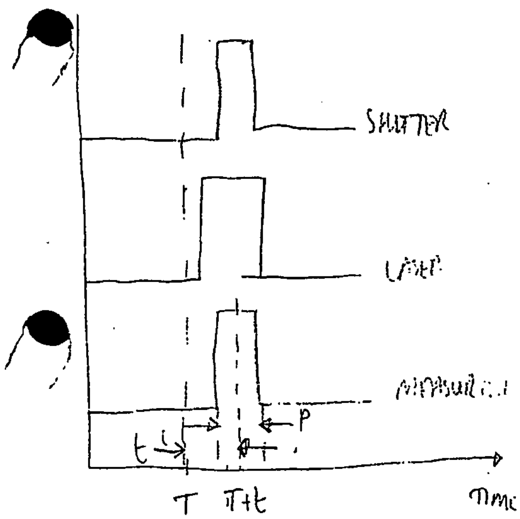


FIG. 64

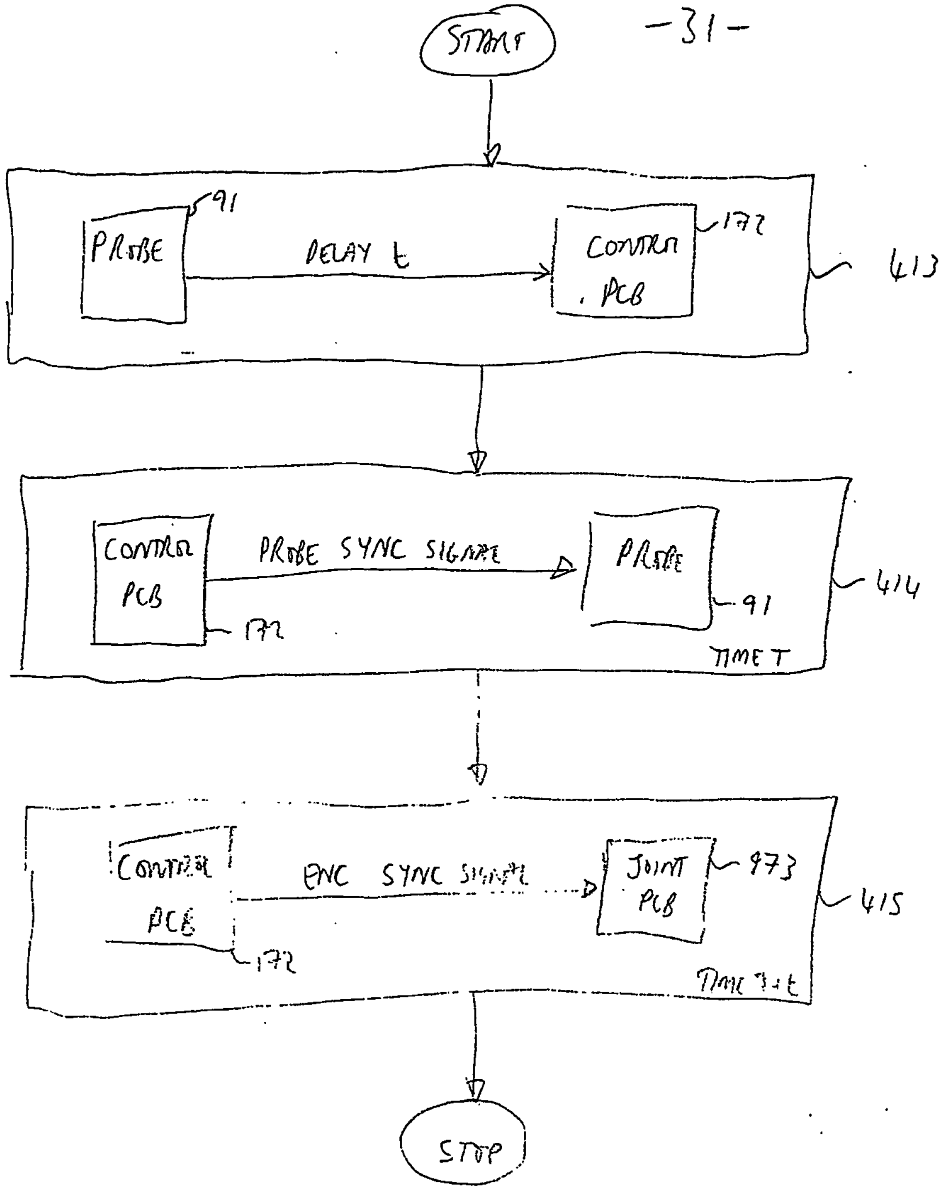

START
PROBE
91
DELAY t
CONTROL PCB
172
413
CONTROL PCB
PROBE SYNC SIGNAL
PROBE
91
172
414
TIME T
CONTROL PCB
ENC SYNC SIGNAL
JOINT PCB
473
415
172
TIME T+t
STOP

FIG. 45

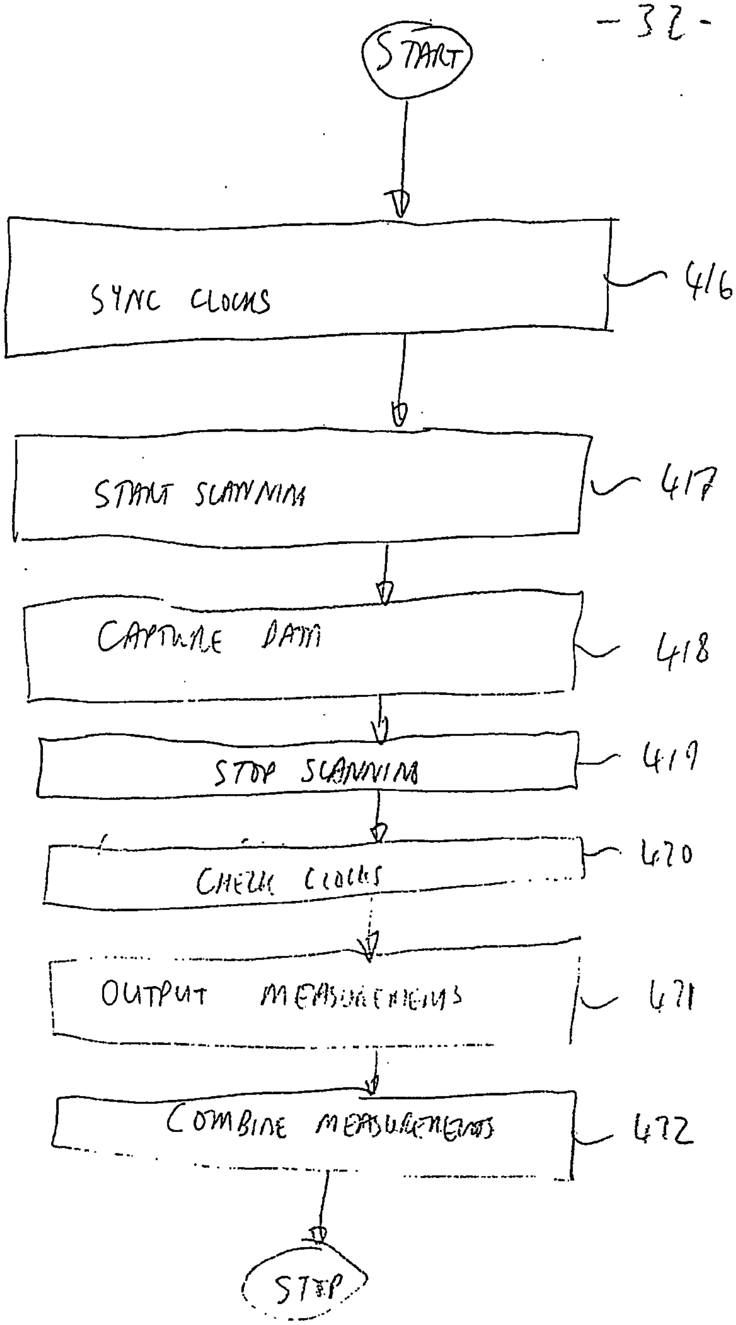

START
SYNC CLOCKS
416
START SCANNING
417
CAPTURE DATA
418
STOP SCANNING
419
CHECK CLOCKS
420
OUTPUT MEASUREMENTS
421
COMBINE MEASUREMENTS
422
STOP

FIG 46

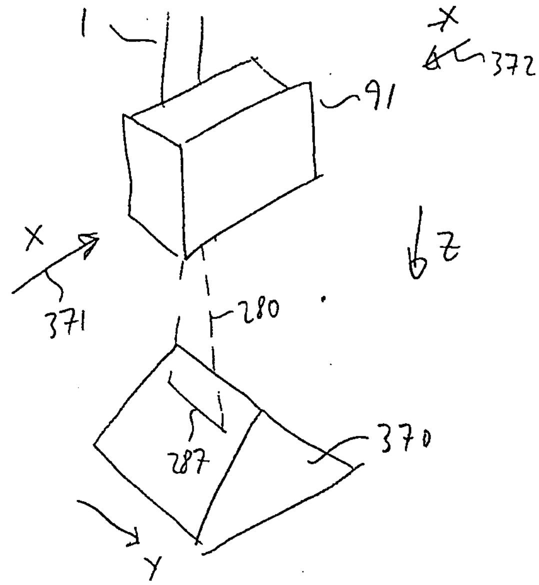


FIG. 47

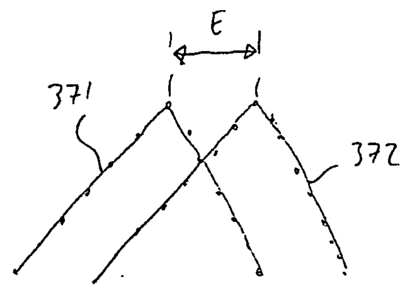


FIG. 48

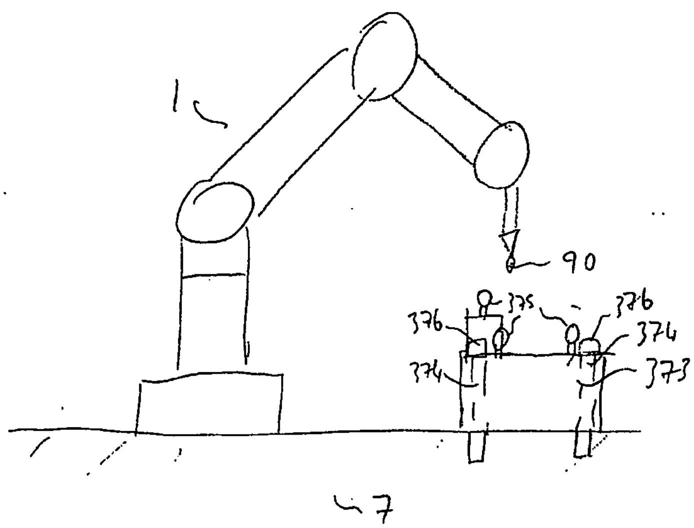


FIG. 49

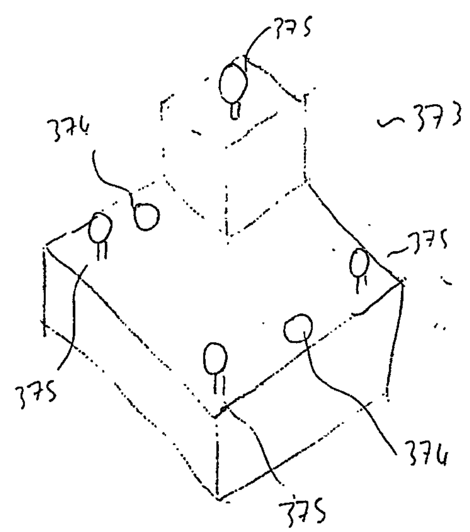


FIG. 50

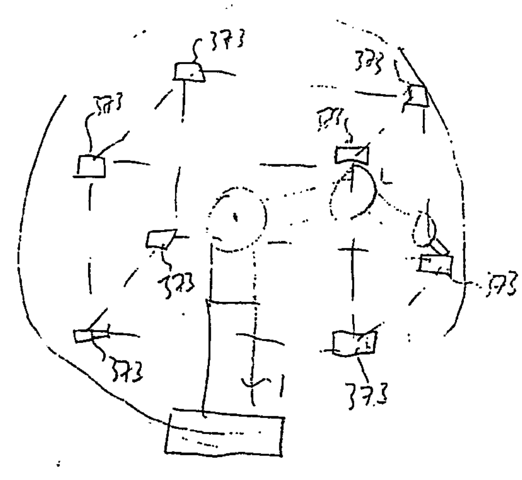


FIG. 51

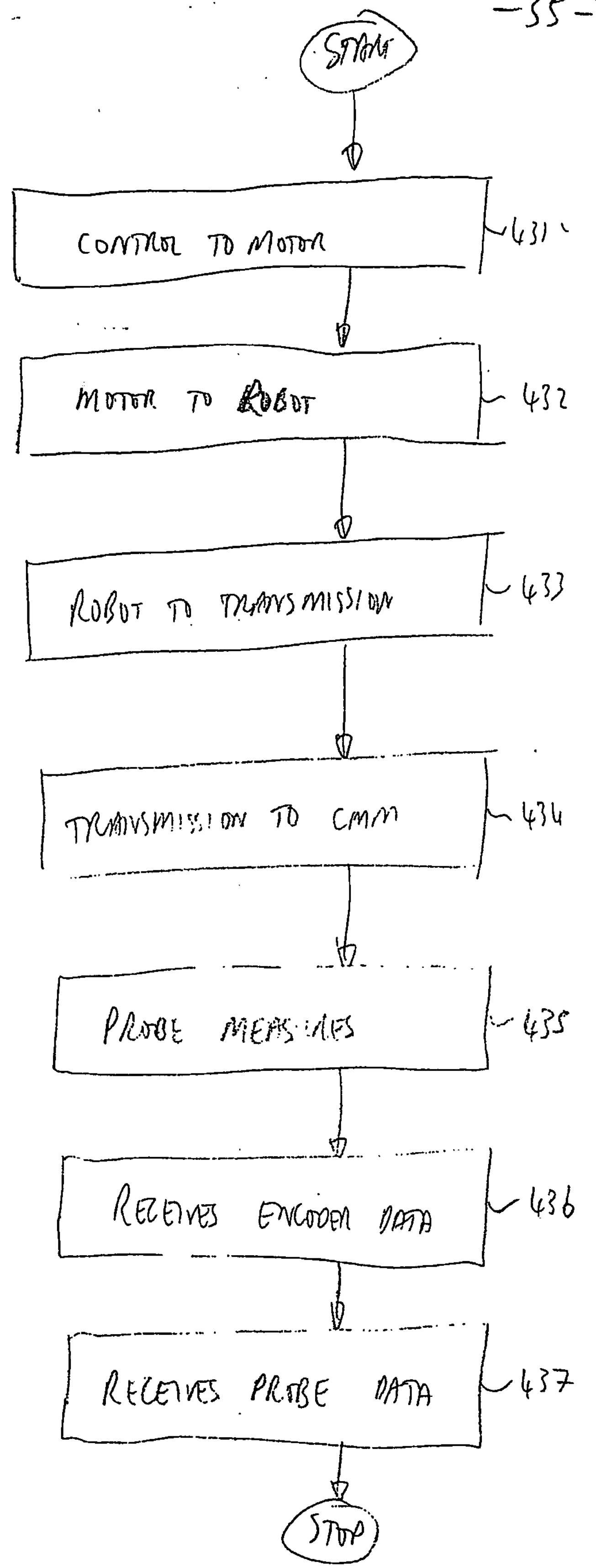

START
CONTROL TO MOTOR
431
MOTOR TO ROBOT
432
ROBOT TO TRANSMISSION
433
TRANSMISSION TO CMM
434
PROBE MEASURES
435
RECEIVES ENCODER DATA
436
RECEIVES PROBE DATA
437
STOP

FIG. 52